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Physics

for Cambridge IGCSE™

COURSEBOOK

David Sang, Mike Follows & Sheila Tarpey

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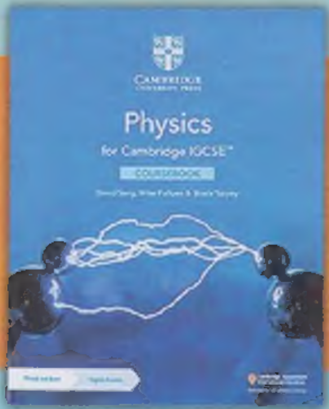
Contents

How to use this series

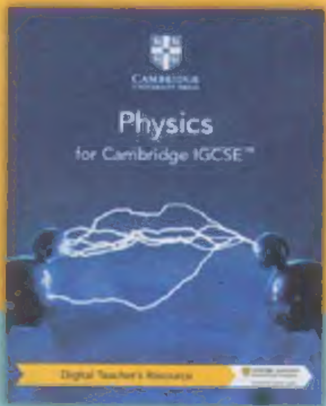
We offer a comprehensive, flexible array of resources for the Cambridge IGCSE™ Physics syllabus. We provide targeted support and practice for the specific challenges we've heard that students face: learning science with English as a second language; learners who find the mathematical content within science difficult; and developing practical skills.

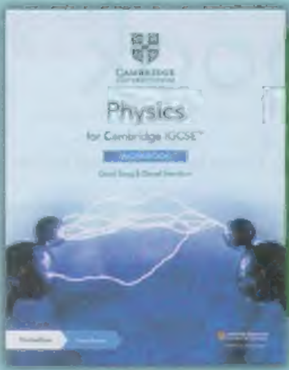


The coursebook provides coverage of the full Cambridge IGCSE Physics syllabus. Each chapter explains facts and concepts, and uses relevant real-world examples of scientific principles to bring the subject to life. Together with a focus on practical work and plenty of active learning opportunities, the coursebook prepares learners for all aspects of their scientific study. At the end of each chapter, examination-style questions offer practice opportunities for learners to apply their learning.

The digital teacher's resource contains detailed guidance for all topics of the syllabus, including common misconceptions identifying areas where learners might need extra support, as well as an engaging bank of lesson ideas for each syllabus topic. Differentiation is emphasised with advice for identification of different learner needs and suggestions of appropriate interventions to support and stretch learners. The teacher's resource also contains support for preparing and carrying out all the investigations in the practical workbook, including a set of sample results for when practicals aren't possible.

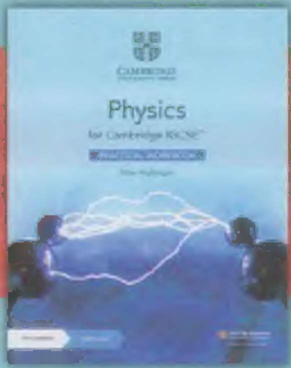
The teacher's resource also contains scaffolded worksheets and unit tests for each chapter. Answers for all components are accessible to teachers for free on the Cambridge GO platform.





The skills-focused workbook has been carefully constructed to help learners develop the skills that they need as they progress through their Cambridge IGCSE Physics course, providing further practice of all the topics in the coursebook. A three-tier, scaffolded approach to skills development enables learners to gradually progress through 'focus', 'practice' and 'challenge' exercises, ensuring that every learner is supported. The workbook enables independent learning and is ideal for use in class or as homework.

The Cambridge IGCSE practical workbook provides learners with additional opportunities for hands-on practical work, giving them full guidance and support that will help them to develop their investigative skills. These skills include planning investigations, selecting and handling apparatus, creating hypotheses, recording and displaying results, and analysing and evaluating data.



Mathematics is an integral part of scientific study, and one that learners often find a barrier to progression in science. The Maths Skills for Cambridge IGCSE Physics write-in workbook has been written in collaboration with the Association of Science Education, with each chapter focusing on several maths skills that learners need to succeed in their Physics course.

Our research shows that English language skills are the single biggest barrier to learners accessing international science. This write-in workbook contains exercises set within the context of Cambridge IGCSE Physics topics to consolidate understanding and embed practice in aspects of language central to the subject. Activities range from practising using comparative adjectives in the context of measuring density, to writing a set of instructions using the imperative for an experiment investigating frequency and pitch.

How to use this book

Throughout this book, you will notice lots of different features that will help your learning. These are explained below.

LEARNING INTENTIONS

These set the scene for each chapter, help with navigation through the coursebook and indicate the important concepts in each topic. These begin with 'In this chapter you will:'.

In the learning intentions table, Supplement content is indicated with a large arrow and a darker background, as in the example here.

GETTING STARTED

This contains questions and activities on subject knowledge you will need before starting the chapter.

SCIENCE IN CONTEXT

This feature presents real-world examples and applications of the content in a chapter, encouraging you to look further into topics that may go beyond the syllabus. There are discussion questions at the end which look at some of the benefits and problems of these applications.

EXPERIMENTAL SKILLS

This feature focuses on developing your practical skills. They include lists of equipment required and any safety issues, step-by-step instructions so you can carry out the experiment, and questions to help you think about what you have learned.

KEY WORDS

Key vocabulary is highlighted in the text when it is first introduced, and definitions are given in boxes near the vocabulary. You will also find definitions of these words in the Glossary at the back of this book.

Supplement content: Where content is intended for learners who are studying the Supplement content of the syllabus as well as the Core, this is indicated in the main text using the arrow and the bar, as on the right here, and the text is in blue. You may also see the blue text with just an arrow (and no bar), in boxed features such as the Key Words or the Getting Started. Symbols in blue are also supplementary content.

Questions

Appearing throughout the text, questions give you a chance to check that you have understood the topic you have just read about. The answers to these questions are accessible to teachers for free on the Cambridge GO site.

ACTIVITY

Activities give you an opportunity to check your understanding throughout the text in a more active way, for example by creating presentations, posters or taking part in role plays. When activities have answers, teachers can find these for free on the Cambridge GO site.

KEY EQUATIONS

Important equations which you will need to learn and remember are given in these boxes.

[illegible]

Command words that appear in the syllabus and might be used in exams are highlighted in the exam-style questions. In the margin, you will find the Cambridge International definition. You will also find these definitions in the Glossary

SELF/PEER ASSESSMENT

At the end of some activities and experimental skills boxes, you will find opportunities to help you assess your own work, or that of your classmates, and consider how you can improve the way you learn

[illegible]

Wherever you need to know how to use an equation to carry out a calculation, there are worked example boxes to show you how to do this.

[illegible]

These activities ask you to think about the approach that you take to your work, and how you might improve this in the future.

[illegible]

Projects allow you to apply your learning from the whole chapter to group activities such as making posters or presentations, or performing in debates. They may give you the opportunity to extend your learning beyond the syllabus if you want to.

[illegible]

There is a summary of key points at the end of each chapter

Supplement content is indicated with a large arrow in the margin and a darker background, as here

EXAM-STYLE QUESTIONS

Questions at the end of each chapter provide more demanding exam-style questions, some of which may require use of knowledge from previous chapters. The answers to these questions are accessible to teachers for free on the Cambridge GO site

[illegible]

The summary checklists are followed by 'I can' statements which match the Learning intentions at the beginning of the chapter. You might find it helpful to rate how confident you are for each of these statements when you are revising. You should revisit any topics that you rated 'Needs more work' or 'Almost there'.

[illegible]	[illegible]	Needs more work	Almost there	Confident to move on
[illegible]				
Supplement				

Introduction

Studying physics

Why study physics? Some people study physics for the simple reason that they find it interesting. Physicists study matter, energy and their interactions. They might be interested in observing the tiniest sub-atomic particles, or understanding the vastness of the Universe itself.

On a more human scale, physicists study materials to try to predict and control their properties. They study the interactions of radiation with matter, including the biological materials we are made of.

Other people are more interested in the applications of physics. They want to know how it can be used, perhaps in an engineering project, or for medical purposes. Depending on how our knowledge is applied, it can make the world a better place.

Some people study physics as part of their course because they want to become some other type of scientist – perhaps a chemist, biologist or geologist. These branches of science draw a great deal on ideas from physics, and physics may draw on them.

Thinking physics

How do physicists think? One of the characteristics of physicists is that they try to simplify problems – reduce them to their basics – and then solve them by applying some very fundamental ideas. For example, you will be familiar with the idea that matter is made of tiny particles that attract and repel each other and move about. This is a very useful model, which has helped us to understand the behaviour of matter, how sound travels, how electricity flows, and much more.

Once a fundamental idea is established, physicists look around for other areas where it might help to solve problems. One of the surprises of 20th century physics was that, once physicists had begun to understand the fundamental particles of which atoms are made, they realised that this helped to explain the earliest moments in the history of the Universe, at the time of the Big Bang.

Medicine is often seen as a biological career but this doctor will use many applications of physics, from X-rays to robotic limbs, in her work.

Physics relies on mathematics. Physicists measure quantities and analyse data. They invent mathematical models – equations and so on – to explain their findings. In fact, a great deal of mathematics has been developed by physicists to help them to understand their experimental results. An example of this is the work of Edward Witten, who designed new mathematical tools to unify different versions of superstring theory – a theory which tries to unite all the forces and particles you are learning about.

Computers have made a big difference in physics, allowing physicists to process vast amounts of data rapidly. Computers can process data from telescopes, control distant spacecraft and predict the behaviour of billions of atoms in a solid material.

In April 2019 the first pictures were released of a black hole. The central area is so dense that light cannot escape it. The image was the result of hundreds of scientists using a network of radio telescopes around the world, processing many petabytes of data – 1 petabyte is equal to 1 million gigabytes or 1×10^{15} bytes

The more you study physics, the more you will come to realise how the ideas join up. Indeed, the ultimate goal for many physicists is to link all ideas into one unifying 'theory of everything'.

Stephen Hawking was a brilliant young student when he was diagnosed with motor neurone disease. He was expected to live only a few years, but at the time of his death at 76 he was still working as a professor at Cambridge University. One of his main aims was to unite relativity (which explains the very large) and quantum physics (which explains the very small)

Hawking came to believe this would not happen, but was glad about this: 'I'm now glad that our search for understanding will never come to an end, and that we will always have the challenge of new discovery. Without it, we would stagnate.'

Using physics

The practical applications of physics are far reaching. Many physicists work in economics and finance, using ideas from physics to predict how markets will change. Others use their understanding of particles in motion to predict how traffic will flow, or how people will move in crowded spaces. This type of modelling can be used to help us understand the spread of pathogens, such as the virus which caused the 2020 Covid-19 pandemic.

Physics is being used to find solutions for the world's major problems. New methods of generating electricity without adding to greenhouse gas emissions are helping to reduce our dependence on fossil fuels. Developments in battery technology allow us to store electrical energy, making electric vehicles a reality

If this child drives it will probably be in an electric vehicle like this one. Many countries aim to phase out polluting, fossil fuel powered vehicles by the middle of the 21st century. Physicists are improving car design and battery life to make this feasible

Joining in

So, when you study physics, you are doing two things.

i You are joining in with a big human project – learning more about the world around us and applying that knowledge.

ii At the same time, you are learning to think like a physicist – how to apply some basic ideas, how to look critically at data, and how to recognise underlying patterns. Whatever path you take, these skills will remain with you and help you make sense of the rapidly changing world in which we live.

Chapter 1
Making measurements

IN THIS CHAPTER YOU WILL:

- learn how to take measurements of length, volume and time
- perform experiments to determine the density of an object
- predict whether an object will float

[illegible]

In pairs, either take the measurements or write down how you would do the following:

- measure the length, width and thickness of this book and work out its volume
- measure the thickness of a sheet of paper that makes up this book
- measure the length of a journey (for example, on a map) that is not straight.

Now discuss how you would work out the density of:

- a regular-shaped solid
- an irregular-shaped solid
- a liquid.

ARE WE CLEVERER THA[illegible]

People tend to dismiss people who lived in the past as less intelligent than we are. After all, they used parts of their bodies for measuring distances. A cubit was the length of the forearm from the tip of the middle finger to the elbow. However, the ancient Egyptians knew this varied between people. Therefore, in around 3000 BCE, they invented the royal cubit (Figure 1.1), marked out on a piece of granite and used this as a standard to produce cubit rods of equal length.

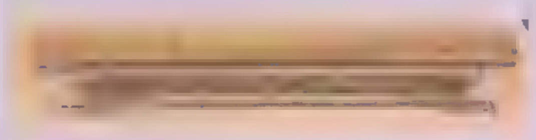


Figure 1.1: Cubit rod.

The Ancient Egyptians were experts at using very simple tools like the cubit rod. This enabled them to build their pyramids accurately. Eratosthenes, a brilliant scientist who lived in Egypt in about 300 BCE, showed the same care and attention to detail. This allowed him to work out that the Earth has a circumference of 40 000 km (Figure 1.2).

In contrast, there are many recent examples where incorrect measurements have led to problems. Although the Hubble Space Telescope had the most precisely shaped mirror ever made, the original images it produced were not as clear as expected. Tiny mistakes in measuring meant that it had the wrong shape and it took a lot of effort to account for these errors.

Figure 1.2: Eratosthenes used shadows and geometry to work out the circumference of the Earth

Discussion questions

1. You cannot always depend on your eyes to judge lengths. Look at Figure 1.3 and decide which line is longer? Check by using a ruler

Figure 1.3: Which line is longer?

2. Eratosthenes may have hired a man to pace the distance between Alexandria and Syene (present-day Aswan) to calculate the Earth's circumference. People have different stride lengths so some people take longer steps than others. Discuss the possible ways that anyone with any stride length could have measured the distance between these towns accurately.

1.1 Measuring length and volume

In physics, we make measurements of many different lengths, for example, the length of a piece of wire, the height of liquid in a tube, the distance moved by an object, the diameter of a planet or the radius of its orbit. In the laboratory, lengths are often measured using a ruler (such as a metre ruler).

Measuring lengths with a ruler is a familiar task. But when you use a ruler, it is worth thinking about the task and just how reliable your measurements may be. Consider measuring the length of a piece of wire (Figure 1.4).

- The wire must be straight, and laid closely alongside the ruler. (This may be tricky with a bent piece of wire.)
- Look at the ends of the wire. Are they cut neatly, or are they ragged? Is it difficult to judge where the wire begins and ends?
- Look at the markings on the ruler. They are probably 1 mm apart, but they may be quite wide. Line one end of the wire up against the zero on the scale. Because of the width of the mark, this may be awkward to judge.
- Look at the other end of the wire and read the scale. Again, this may be tricky to judge.

Now you have a measurement, with an idea of how **precise** it is. You can probably determine the length of the wire to within a millimetre. But there is something else to think about – the ruler itself. How sure can you be that it is correctly **calibrated**? Are the marks at the ends of a metre ruler separated by exactly one metre? Any error in this will lead to an inaccuracy (probably small) in your result.

The point here is to recognise that it is always important to think critically about the measurements you make, however straightforward they may seem. You have to consider the method you use, as well as the instrument (in this case, the ruler).

Figure 1.4: Simple measurements still require careful technique, for example, finding the length of a wire.

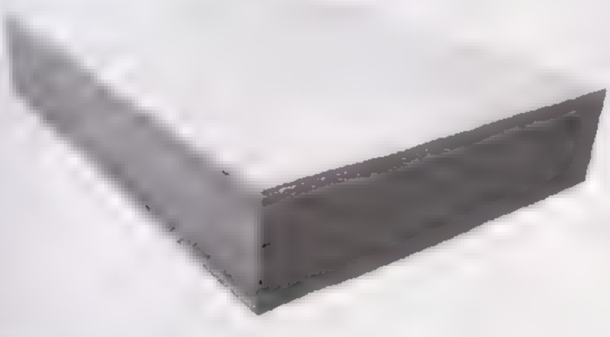
standard: is an absolute or primary reference or measurement

precise: when several readings are close together when measuring the same value

calibrated: should agree closely with a standard or agrees when a correction has been applied

More measurement techniques

If you have to measure a small length, such as the thickness of a wire, it may be better to measure several thicknesses and then calculate the average. You can use the same approach when measuring something very thin, such as a sheet of paper. Take a stack of 500 sheets and measure its thickness with a ruler (Figure 1.5). Then divide by 500 to find the thickness of one sheet.



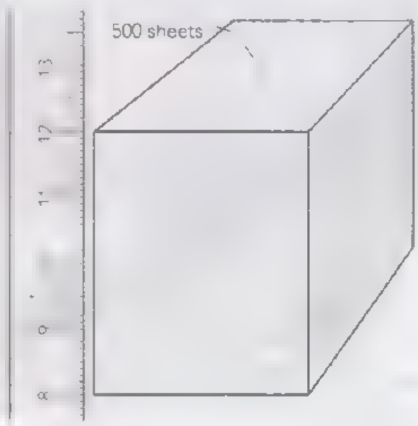


Figure 1.5: Making multiple measurements

For some measurements of length, such as curved lines, it can help to lay a thread along the line. Mark the thread at either end of the line and then lay it along a ruler to find the length. This technique can also be used for measuring the circumference of a cylindrical object such as a wooden rod or a measuring cylinder.

Measuring volumes

There are two approaches to measuring volumes, depending on whether or not the shape is regular

For a cube or cuboid, such as a rectangular block, measure the length, width and height of the object and multiply the measurements together. For objects of other regular shapes, such as spheres or cylinders, you may have to make one or two measurements and then look up the equation for the **volume**.

For liquids, measuring cylinders can be used as shown in Figure 1.6. (Recall that these are designed so that you look at the scale horizontally, not at an oblique angle, and read the level of the bottom of the **meniscus**.) The meniscus is the curved upper surface of a liquid, caused by surface tension. It can curve up or down but the surface of water in a measuring cylinder curves downwards. Think carefully about the choice of cylinder. A 1 litre (or a 1 dm^3) cylinder is unlikely to be suitable for measuring a small volume such as 5 cm^3. You will get a more accurate answer using a 10 cm^3 cylinder.

Figure 1.6: A student measuring the volume of a liquid. Her eyes are level with the scale so that she can accurately measure where the meniscus meets the scale

Measuring volume by displacement

Most objects do not have a regular shape, so we cannot find their volumes simply by measuring the lengths of their sides. Here is how to find the volume of an irregularly shaped object. This technique is known as measuring volume by **displacement**.

- Select a measuring cylinder that is about three or four times larger than the object. Partially fill it with water (Figure 1.7), enough to cover the object. Note the volume of the water
- **Immerse** the object in the water. The level of water in the cylinder will increase, because the object pushes the water out of the way and the only way it can move is upwards. The increase in its volume is equal to the volume of the object

Units of length and volume

In physics, we generally use SI units (this is short for Le Système International d'Unités or The International System of Units). The SI unit of length is the metre (m). Table 1.1 shows some alternative units of length, together with some units of volume. Note that the litre and millilitre are not official SI units of volume, and so are not used in this book. One litre (1 l) is the same as 1 dm^3, and one millilitre (1 ml) is the same as 1 cm^3

volume: the space occupied by an object

meniscus: curved upper surface of a liquid

displace: moving something to another place so water is moved out of the way (upwards) when an object is lowered into it

immerse: to cover something in a fluid (usually water) so that the object is submerged

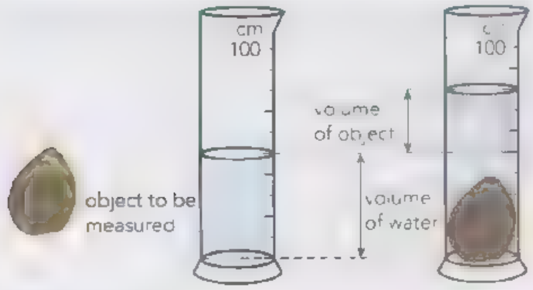


Figure 1.7: Measuring volume by displacement.

Quantity	Units
length	metre (m) 1 decimetre (dm) = 0.1 m 1 centimetre (cm) = 0.01 m 1 millimetre (mm) = 0.001 m 1 micrometre (µm) = 0.000 001 m 1 kilometre (km) = 1000 m
volume	cubic metre (m^3) 1 cubic centimetre (cm^3) = 0.000 001 m^3 1 cubic decimetre (dm^3) = 0.001 m^3

Table 1.1: Some units of length and volume in the SI system.

Questions

1 The volume of a piece of wood which floats in water can be measured as shown in Figure 1.8.
   - **a** Write a paragraph to describe the procedure
   - **b** State the volume of the wood

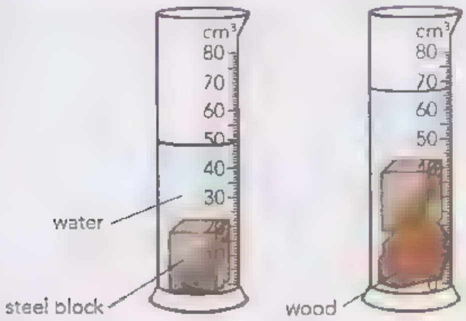


Figure 1.8: Measuring the volume of an object that floats.

2 A stack of paper contains 500 sheets of paper. The stack has dimensions of 0.297 m × 21.0 cm × 50.0 mm
   - **a** What is the thickness of one sheet of paper?
   - **b** What is the volume of the stack of paper in cm^3?

1.2 Density

Our eyes can deceive us. When we look at an object, we can judge its volume. However, we can only guess its mass. We may guess incorrectly, because we misjudge the density. You may offer to carry someone's bag, only to discover that it contains heavy books. A large box of chocolates may have a mass of only 200 g.

The mass of an object is the quantity (amount) of matter it is made of. Mass is measured in kilograms. But density is a property of a material. It tells us how concentrated its mass is. You will learn more about the meaning of mass and how it differs from weight in Chapter 3.

In everyday speech, we might say that lead is heavier than wood. We mean that, given equal volumes of lead and wood, the lead is heavier. In scientific terms, the density of lead is greater than the density of wood. So we define density as shown, in words and as an equation.

Density is the mass per unit volume for a substance.

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

$$\rho = \frac{m}{V}$$

mass: the quantity of matter a body is composed of; mass causes the object to resist changes in its motion and causes it to have a gravitational attraction for other objects

density: the ratio of mass to volume for a substance

weight: the downward force of gravity that acts on an object because of its mass

The symbol for density is ρ, the Greek letter rho. The SI unit of density is kg/m^3 (kilograms per cubic metre). You may come across other units, as shown in Table 1.2

Unit of mass	Unit of volume	Unit of density	Density of water
kilogram, kg	cubic metre, m^3	kilograms per cubic metre	1000 kg/m^3
kilogram, kg	cubic decimetre, dm^3	kilograms per cubic decimetre	1.0 kg/dm^3
gram, g	cubic centimetre, cm^3	grams per cubic centimetre	1.0 g/cm^3

Table 1.2: Units of density.

Values of density

Some values of density are shown in Table 1.3. Gases have much lower densities than solids or liquids.

An object that is less dense than water will float. Ice is less dense than water which explains why icebergs float in the sea, rather than sinking to the bottom. Only about one tenth of an iceberg is above the water surface. If any part of an object is above the water surface, then it is less dense than water.

	Material	Density / kg/m^3
Gases	air	1.29
	hydrogen	0.09
	helium	0.18
	carbon dioxide	1.98
Liquids	water	1000
	alcohol (ethanol)	790
	mercury	13 600
Solids	ice	920
	wood	400–1200
	polyethene	910–970
	glass	2500–4200
	steel	7500–8100
	lead	11 340
	silver	10 500
	gold	19 300

Table 1.3: Densities of some substances. For gases, these are given at a temperature of 0 °C and a pressure of 1.0×10^5 Pa.

Many materials have a range of densities. Some types of wood, for example, are less dense than water and will float. Other types of wood (such as mahogany) are more dense and will sink. The density depends on the nature of the wood (its composition).

Gold is denser than silver. Pure gold is a soft metal, so jewellers add silver to make it harder. The amount of silver added can be judged by measuring the density.

It is useful to remember that the density of water is 1000 kg/m^3, 1.0 kg/dm^3 or 1.0 g/cm^3.

Calculating density

To calculate the density of a material, we need to know the mass and volume of a sample of the material.

[illegible]

A sample of ethanol has a volume of 240 cm^3.

Its mass is found to be 190.0 g. What is the density of ethanol?

Step 1: Write down what you know and what you want to know.

mass $m = 190.0$ g

volume $V = 240$ cm^3

density $\rho = ?$

Step 2: Write down the equation for density, substitute values and calculate ρ.

$$\rho = \frac{m}{V}$$

$$= \frac{190\ \text{g}}{240\ \text{cm}^3}$$

$$= 0.79\ \text{g/cm}^3$$

Answer

Density of ethanol = 0.79 g/cm^3

Measuring density

The easiest way to determine the density of a substance is to find the mass and volume of a sample of the substance.

For a solid with a regular shape, find its volume by measurement (see Section 1.1). Find its mass using a balance. Then calculate the density.

Questions

3 A brick is shown in Figure 1.9. It has a mass of 2.8 kg.

Figure 1.9: A brick labelled with its dimensions.

   a Give the dimensions of the brick in metres.
   b Calculate the volume of the brick.
   c Calculate the density of the brick.

4 A box full of 35 matches has a mass of 6.77 g. The box itself has a mass of 3.37 g.
   a What is the mass of one match in grams?
   b What is the volume (in cm^3) of each match. A match has dimensions of 42 mm × 2.3 mm × 2.3 mm?
   c What is the density of the matches?
   d How do you know if these matches will float?

5 The Earth has a mass of 6×10^{24} kg and a radius of about 6400 km. What is the density of the Earth (in kg/m^3)? The volume of a sphere is given by the equation $V = \frac{4}{3}\pi r^3$, where r is the radius.

6 40 drawing pins (thumb tacks) like those shown in Figure 1.10 have a mass of 17.55 g. What is the volume (in mm^3) of one pin when they are made of metal with a density of 8.7 g/cm^3?

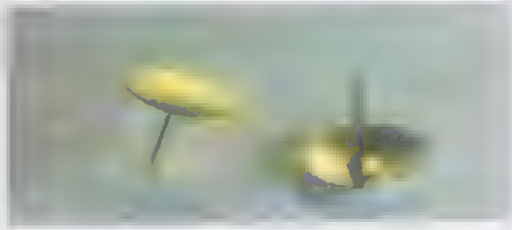


Figure 1.10: A pair of drawing pins (thumb tacks)

7 A young girl from the Kayan people in northern Thailand wears a neck ring made of brass (Figure 1.11). It looks as if there are 21 individual rings but the ring is actually one continuous length of brass fashioned (bent) into a coil. The height of the brass coil is 12 cm and its average circumference is 40 cm. Neck rings are usually only removed to be replaced with a bigger one as the girl grows. However, we can estimate the mass of this neck ring without removing it.

Figure 1.11: A Kayan girl wearing a neck ring

a What looks like 21 individual rings around the girl's neck is actually 21 turns of a coil of brass. Each turn has a circumference of 40 cm. Calculate (in cm) the total length of brass used to make the girl's neck ring.

b The coil has a height of 12 cm and the coil has 21 turns. Calculate the radius of the brass in cm.

c If the brass coil is unwound from the girl's neck and straightened out, it would be a long, thin, cylinder. Calculate the volume of this cylinder in cm^3. The volume of a cylinder is given by the equation $V = \pi r^2 h$, where r = radius and h = height.

d Calculate the mass of brass used to make the neck ring and express your answer in kg. The density of brass = 8.73 g/cm^3.

Finding the density of a liquid

Figure 1.12 shows one way to find the density of a liquid. Place a measuring cylinder on a balance. Set the balance to zero. Now pour liquid into the cylinder. Read the volume from the scale on the cylinder. The balance shows the mass.

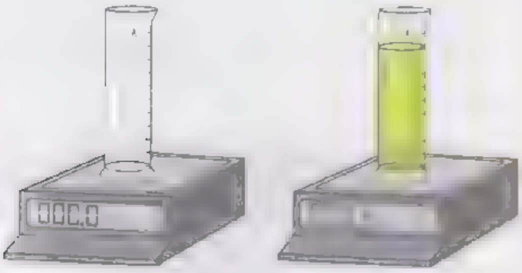


Figure 1.12: Measuring the mass of a liquid

When liquids with different densities are poured into the same container, they will arrange themselves so that the liquid with the lowest density will be at the top and the ones with the highest density will be at the bottom. This is because the denser liquids displace the less dense liquids. This is easier to see when each liquid is given a different colour. In Figure 1.13, the green liquid is less dense than the red liquid and so on.

When a distinct layer forms in a mixed solution, the liquids are said to be immiscible, which means they do not mix. This is why oil floats on water. However, not all liquids stay separated so you would be disappointed if you tried this at home with squash and water, for example.

When liquids mix, it is usually because one liquid dissolves in the other. For example, orange squash is a concentrated syrup that is diluted by dissolving it in water.

Figure 1.13: Liquid density towers

Apart from making colourful liquid density towers, do variations in the density of liquids have practical consequence? In Chapter 11, you will learn about convection currents in fluids (liquids and gases), which are driven by differences in density. These convection currents include the thermohaline circulation in the oceans. Colder and saltier water sinks, displacing (pushing up) warmer and less salty water.

ACTIVITY 1.1

Finding the density of a regularly shaped solid

In pairs, create a worksheet on the computer for finding the density of a regularly shaped solid object (for example, a rectangular block) using a ruler and a mass balance. Your worksheet should include:

- a method for measuring the mass and working out the volume
- the equation for calculating density
- a table to record the data.

You could include an optional task to work out the density of a liquid.

After your allotted time, another pair is going to test a copy of your worksheet (perhaps by doing the experiment). They are going to add any steps that are missing or make suggestions to make your worksheet clearer. When you get your worksheet returned, edit and save a new version of it.

CONTINUED

Finding the density of an irregularly shaped solid

Before you start, make a copy of your previous worksheet and save it under a new name. Some of what you included in the previous worksheet can be kept and some will need to be edited.

In pairs, create a worksheet for finding the density of an irregularly shaped solid object using a mass balance, a measuring cylinder, some thread, a pair of scissors and a eureka can (if you have access to one). Your method explaining how to measure the mass and how to calculate the density should be the same. However, you should:

- explain how to measure volume by displacement
- say something about choosing a suitably sized measuring cylinder
- change your previous table

You could include an optional task to work out the density of an irregularly shaped solid object that is less dense than water. Finding its mass and calculating the density is straightforward. The challenging part is explaining how to work out the volume of an object that floats.

Design a flowchart or decision-tree (optional)

Design a flowchart or decision-tree for use by anyone who wants to work out the density of any liquid or any solid object. Ensure that your flowchart includes enough information so that someone could take the measurements. Ask your partner or someone else who has completed the first two parts to check and correct your flowchart.

Write down one thing that you did really well in this activity

Write down one thing that you will try to do better next time. How will you do this?

1.3 Measuring time

The athletics coach in Figure 1.14 is using his stopwatch to time a sprinter. For a sprinter, a fraction of a second (perhaps just 0.01 s) can make all the difference between winning and coming second or third. It is different in a marathon, where the race lasts for more than two hours and the runners are timed to the nearest second

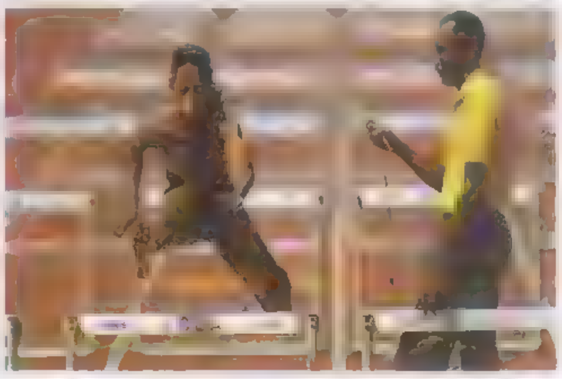


Figure 1.14: An athletics coach uses a stopwatch to time a hurdler, who can then learn whether she has improved.

How dense can you be?

In groups of three, write a method showing how you could work out your own density, or that of a friend or of a younger sibling. Alternatively, plan out your strategy and be prepared to share it with the class. There are at least two methods: a dry method and a wet method. Discuss one or both of them.

You will need to include

- a method that is detailed enough for someone to follow (this should include advice about how a measurement should be taken)
- any calculations
- possible sources of uncertainty in the measurements
- what you expect your answer to be.

If you actually carried out the experiment, comment on how close your measurement was to what you expected.

In the laboratory, you might need to record the temperature of a container of water every minute, or find out how long an electric current is flowing. For measurements like these, stopclocks and stopwatches can be used. You may come across two types of timing device.

An analogue clock (Figure 1.15) is like a traditional clock whose hands move round the clock's face. You find the time by looking at where the hands are pointing on the scale. It can be used to measure time intervals to no better than the nearest second.

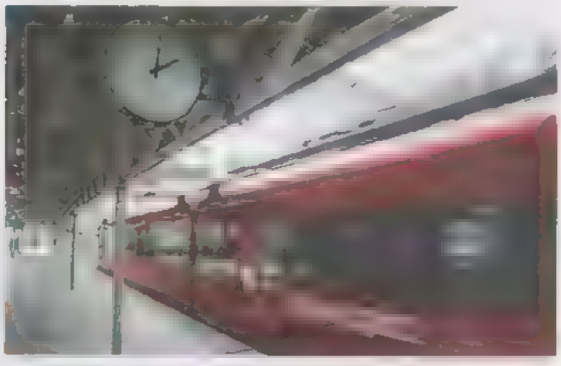


Figure 1.15: An analogue clock.

A digital clock (Figure 1.16) or stopwatch is one that gives a direct reading of the time in numerals. For example, a digital clock might show a time of 9.58 s. A digital clock records time to a precision of at least one hundredth of a second. You would never see an analogue watch recording times in the Olympic Games.

Figure 1.16: A digital clock started when the gun fired and stopped 9.58 s later when Usain Bolt crossed the finishing line to win the 100 m at the 2009 World Championships in world record time.

analogue display has hands (or a needle) and is often not very precise

digital display shows numbers and is often precise

When studying motion, you may need to measure the time taken for a rapidly moving object to move between two points. In this case, you might use a device called a light gate connected to an electronic timer. This is similar to the way in which runners are timed in major athletics events. An electronic timer starts when the marshal's gun is fired, and stops as the runner crosses the finishing line.

You will learn more about how to use electronic timing instruments in Chapter 2.

Measuring short intervals of time

Figure 1.17 shows a typical lab pendulum. A mass, called a plumb bob, hangs on the end of a string. The string is clamped tightly at the top between two wooden jaws. If you pull the bob gently to one side and release it, the pendulum will swing from side to side.

The time for one oscillation of a pendulum (when it swings from left to right and back again) is called its period. A single period is usually too short a time to measure accurately. However, because a pendulum swings at a steady rate, you can use a stopwatch to measure the time for a large number of oscillations (perhaps 20 or 50), and calculate the average time per oscillation. Any inaccuracy in the time at which the stopwatch is started and stopped will be much less significant if you measure the total time for a large number of oscillations.

plumb bob: a mass (usually lead) hanging from a string to define a vertical line

oscillation: a repetitive motion or vibration

period: the time for one complete oscillation or wave, the time it takes an object to return to its original position

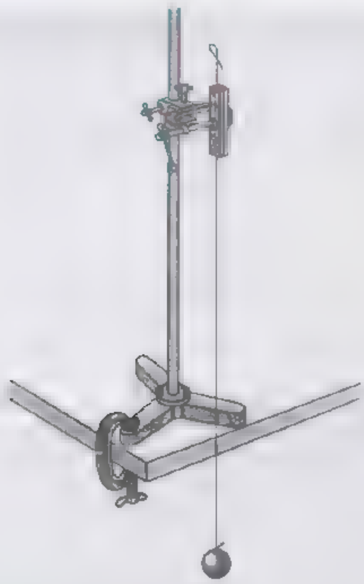


Figure 1.17: A simple pendulum.

Questions

8 High-speed video can record sporting events at a frame rate of 60 frames per second (frame/s).

a What is the time interval between one frame and the next?

b If we can see 24 frame/s as continuous motion, by what factor can the action recorded at 60 frame/s be slowed down and still look continuous?

9 A student was investigating how the period of a pendulum varied with the length of the string and obtained the results in Table 1.4.

Length of string / m	Time for 20 oscillations / s	Time for 1 oscillation / s
0.00	0.0	
0.20	18.1	
0.40	25.1	
0.60	28.3	
0.80	39.4	
1.00	40.5	
1.20	44.4	
1.40	47.9	

Table 1.4

a Why did the student record the time for 20 swings?

b Make a copy of Table 1.4 and, for each length of the pendulum, calculate the time for one oscillation and record the value in the third column of the table.

c Plot a graph of the period of the pendulum against its length (that is, plot the length of the pendulum on the x-axis).

d Use the graph to work out the length of the pendulum when the period is 2 seconds. This is the length of pendulum used in a grandfather clock.

ACTIVITY 1.1

Using a pendulum as a clock

In 1656 the Dutch scientist Christiaan Huygens invented a clock based on a swinging pendulum. Clocks like these were the most precise in the world until the 1930s. One oscillation of a pendulum is defined as the time it takes for a plumb bob at the bottom of the string to return to its original position (Figure 1.18).

You need to develop a worksheet so that students can plot a graph of how the period of oscillation of a pendulum varies with the length of the string. They then need to use the graph to find the length the pendulum needs to be to give a period of one second (useful for a clock). Your worksheet needs to:

Figure 1.18: One oscillation is when the plumb bob swings one way and then the other and returns back to its original position.

- define what an oscillation means (so that a student knows when to start and stop the stopwatch)
- explain why we take the time for 10 or 20 oscillations when we only need the time for one oscillation
- provide a labelled diagram of the assembled apparatus (not just a list of equipment) so that students know how to put the equipment together
- a method (step-by-step instructions)

Swap copies of your worksheet with a classmate. Write down suggestions for any improvements on the worksheet you receive before returning it to its owner. Note down any improvements if you have a class discussion.

In groups of three or four, produce a podcast (no more than five minutes long) on one of the following options

Option 1: Can we build on what we [illegible] about density?

This is opportunity to revise what you have learned about density and then consolidate that knowledge and understanding by applying it to one of the two examples below.

- You must explain how density is calculated, including the equation.
- You should describe how to measure the mass and volume of both regular and irregular shaped objects.
- You could describe how to work out the density of an object that can float.

1 RSS Titanic

It was claimed that the RSS Titanic was unsinkable. However the ship sank in 1912 on its first voyage.

- You must explain why a ship can float despite being made of material that is denser than water.
- You should explain why a ship can sink, in terms of changes in density.
- Do some research to find out about bulkheads in ships. what are they and what are they for? Why did the RSS Titanic sink despite being fitted with bulkheads?

2 Submarines and scuba divers

You could describe one phenomenon that depends on changes or differences in density You could think of your own or select one of these:

- Explain how a submarine or scuba diver moves up and down in the water column (or perhaps explain how a Cartesian diver demonstration works).
- Explain how differences in fluid density can lead to convection (something you will meet in Chapter 11). You might want to go on to discuss how this relates to ocean currents or wind.

Option 2: What was the solution to the longitude problem?

A clock based on a pendulum is impractical on the moving deck of a (sailing) ship but knowing the time is important for navigation as this provides your longitude on a spinning Earth. Lines of longitude are the vertical lines on a map When you move east or west you are changing your longitude; move far enough and you change time zone.

- You must start with a short description of the longitude problem.
- You could describe the various suggested solutions to the longitude problem.
- You could describe the final solution to the longitude problem. For this, you would need to look up John Harrison and his marine chronometer.

Option 3: How did the Ancient Egyptians build their pyramids so accurately?

The pyramids are an incredible feat of engineering, even by today's standards. Using very basic tools, the Egyptians' pyramids are perfectly symmetrical

- You could start by introducing the dimensions of the Giza pyramid and the number of blocks required to build it.

- You cou d explain how the Egyptians managed to get the sides of their pyramids lined up with true north (without a compass) and how they got the base of them absolutely leve (flat) without a (spirit) level.

Option 4: How did Eratosthenes work out the circumference of the Earth?

Eratosthenes was a brilliant scientist He was told that, at the same time every year (12 noon on 21 June), vertica columns in Syene (present day Aswan) cast no shadows while columns where he lived in Alexandria cast shadows. He used this to work out that the Earth is round. Eratosthenes may have hired a man to measure out the distance between Alexandria and Syene.

- You could start with a short biography of Eratosthenes.
- You should explain why the observation with the shadows shows that the Earth is a sphere. You might want to include a diagram like Figure 1.2.
- You should try and show how the man hired by Eratosthenes could have worked out his stride-length (the distance of each step) and kept count of his strides (steps). Think about his possible journey: did he follow a straight line; were there any hills in the way? Could this have introduced errors in measuring the distance between A exandria and Syene?
- Finally, you could show how Eratosthenes did the calculation.

Option 5: How did Archimedes really work out that the goldsmith had replaced some of the gold in Hiero's crown with silver?

Archimedes was probably the most brilliant sc entist of his era. He is supposed to have solved the problem of how to work out the density of the crown while having a bath. Legend has it that he then ran into the streets shouting 'eureka' (I've solved it).

- You could start with a short biography of Archimedes
- You could then describe the usual explanation of how he worked out that some gold had been stolen. Silver is less dense than gold so the same mass of si ver has a bigger volume and will displace a bigger volume of water. However, it would be difficult to measure the difference n volume, especially since bubbles of air cou d cling to the submerged crown and there could be other sources of error.
- You could describe a better method, which uses a mass balance. You would need to exp ain why, when the masses are equal, the balance tips towards the denser mass when lowered into water.
- Gold needs some silver impurity or it would be too soft and would be easy to bend out of shape. Perhaps the goldsmith was fa sely accused? Perhaps this idea could form part of a piece of creative writing (some prose or a play) but be sure to include the physics.

- For your project, write down some thoughts about what you feel went well and areas where you could improve.
- Give yourself a score out of ten for how much you know and understand the phys cs you included. If you scored ten, write down how you could have produced a more ambitious project. If you scored ess, do you need to thoroughly review the materia or are you making careless errors? Write down what concrete steps you need to take to improve for next time.
- Give yourself a score out of ten for the quality of your presentation. Write down what you thought was good about the other presentations or any effective presentation ideas that you might use next time you present.

[illegible]

Length can be measured using a ruler.
The period of one oscillation can be measured by measuring the time for 20 oscillations and then dividing the time by 20.
The volume of a cube or cuboid can be found by measuring the length of the three sides and multiplying the measurements together.
The volume of a liquid can be measured using a measuring cylinder where the bottom of the meniscus appears on the scale when looked at horizontally.
All objects that sink in water displace their own volume of water.
The volume of an irregularly shaped object can be found from the change in the height of liquid in a measuring cylinder when it is immersed in the liquid.
Density is the ratio of mass to volume for a substance: $\rho = \frac{m}{V}$.
The density of water is 1000 kg/m^3 or 1.0 g/cm^3.
Anything less dense than water will float in water and anything denser than water will sink in water.
Ice floats because it is less dense than water.
One liquid will float on top of another liquid if it is less dense.
Time can be measured using a clock or watch.
An analogue clock has hands and can only measure time to the nearest second.
A digital clock displays numbers and records time to a precision of at least one hundredth of a second.

EXAM-STYLE QUESTIONS

Use this table to answer questions 1 and 2.

Metal	Density / g/cm^3
gold	19.30
silver	10.49
lead	11.34

1 Three metal cubes have the same volume but are made of different metals. Each one is lowered into a beaker of water. Use the data in the table to decide which one will cause the biggest rise in water level. **[1]**

A gold
B silver
C lead
D all will cause the same rise in water level

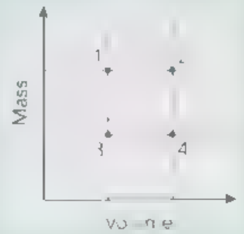
2 Three metal cubes have the same mass but are made of different metals. Each one is lowered into a beaker of water. Use the data in the table to decide which one will cause the biggest rise in water level. [1]

A gold
B silver
C lead
D all will cause the same rise in water level

3 Astronauts land on another planet and measure the density of the atmosphere on the planet surface. They measure the mass of a 500 cm^3 conical flask plus stopper as 457.23 g. After removing the air, the mass is 456.43 g (1 m^3 = 1000 litres). What is the best estimate of the density of the air? [1]

A 0.000 001 6 kg/m^3
B 0.0016 kg/m^3
C 0.16 kg/m^3
D 1.6 kg/m^3

4 The graph shows the mass and volume of several different objects.



Which two objects have the same density? [1]

A 2 and 3 **B** 1 and 4 **C** 2 and 4 **D** 3 and 4

5 A student measures the circumference of a circular copper pipe.

He wraps a length of string four times around the pipe and marks it with ink, as shown in the photograph.

a The student unwraps the string and holds it against a ruler with a centimetre scale.

The photograph shows the first two ink marks on the string.

i Use the photograph to estimate the circumference of the pipe. [1]

ii The student finds that the total length of string for 4 turns is 354 mm. **Calculate** the average (mean) circumference of the pipe using this value. [1]

[Total: 2]

6 **Suggest** how you would work out the thickness of a single sheet of paper if the only measuring device available was a ruler and its smallest division was 1 mm. [1]

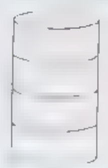
7 What is the mass of a microscope slide that has dimensions of 75 mm × 26 mm × 1 mm and has a density of 2.24 g/cm^3? [2]

8 Four different liquids are poured into a 100 cm^3 measuring cylinder that is 10 cm tall. Each liquid has a different density and each has a different colour.

a Calculate the missing values in the table. [4]

	Liquid	Mass / g	Volume / cm^3	Density / g/cm^3
clear	ethanol	i	20.00	0.79
red	glycerin	20.00	ii	[illegible]
green	olive oil	25.90	28.80	iii
blue	turpentine	30.00	[illegible]	iv

b Copy the diagram below. Using the data from the table above, write down the colour of the liquid you would expect to find in each layer and how thick the layer would be. [2]



Colour of layer	Thickness of layer / cm

9 Metals are denser than water. **Explain** why a metal ship can float. [1]

10 Suggest how you could work out the density of a drawing pin. [3]

calculate: work out from given facts, figures or information

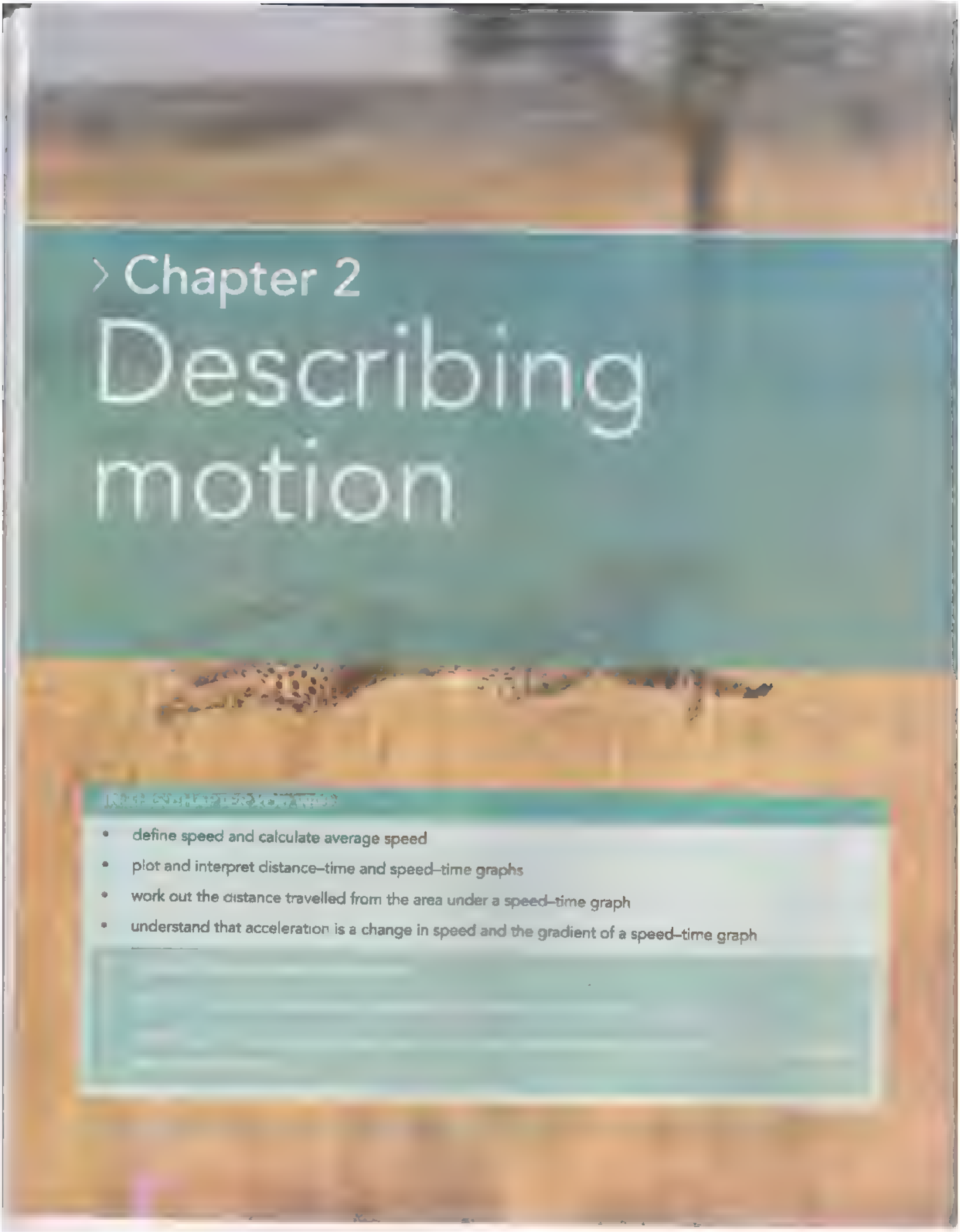
suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/ put forward considerations

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	Almost there	Confident to move on
Measure length, volume and time.	1.1, 1.3			
Calculate the volume of a cube or cuboid from measurements using a ruler.	1.1			
Determine the volume of an irregularly shaped object.	1.1			
Measure the size of tiny objects (for example, the thickness of a sheet of paper, the volume of a drawing pin).	1.1			
Calculate density.	1.2			
Predict whether an object will float or sink in water based on its density.	1.2			
Describe an experiment to find the density of a liquid.	1.2			
Predict whether a liquid will float on top of another liquid if their densities are known and they cannot mix.	1.2			
Describe an experiment to find the density of a cube or cuboid.	1.2			
Describe an experiment to find the density of an irregularly shaped object.	1.2			
Describe the differences between analogue and digital watches or clocks.	1.3			



> Chapter 2

Describing motion

[illegible]

- define speed and calculate average speed
- plot and interpret distance–time and speed–time graphs
- work out the distance travelled from the area under a speed–time graph
- understand that acceleration is a change in speed and the gradient of a speed–time graph

Work in pairs.

On your own, quickly sketch a distance–time graph, perhaps based on your journey to school. Then ask your partner to write a description of it on a separate sheet of paper. Discuss each other's answers.

Sketch a speed–time graph for a sprinter running the 100 m in a time of 9.58 s. Label it with as much information as you know. Show how your graph could be used to work out the sprinter's acceleration at the start of the race and the distance he travelled. Compare your sketch with your partner's and add to or correct your own work. Be prepared to share your thoughts with the class

AROUND THE WORLD IN 80 DAYS

The first known circumnavigation (trip around the world) was completed by a Spanish ship on 8 September 1522. It took more than three years. The French writer Jules Verne wrote the book *Le tour du monde en quatre-vingts jours* (which means *Around the World in Eighty Days*) in 1873. In honour of the writer, the Jules Verne Trophy is a prize for the fastest circumnavigation by a yacht, now held by the yacht IDEC Sport, which did it in just under 41 days in 2017. In 2002, the American Steve Fossett was the first to make a solo circumnavigation in a balloon, without stopping, taking just over 13 days. In 2006, he flew the Virgin Atlantic GlobalFlyer (Figure 2.1), the first fixed-wing aircraft to go around the world without stopping or refuelling. It took him just under three days. Hypersonic jets are being developed that could fly at 1.7 km per second so they could circumnavigate the globe in an incredible six and a half hours

Figure 2.1: The Virgin Atlantic GlobalFlyer passes over the Atlas Mountains

Sometimes these epic adventures inspire those who do them to campaign for a better world. The British sailor Ellen MacArthur (Figure 2.2) is just such a person. She held the world record for the fastest solo circumnavigation, achieved on 7 February 2005. However, she retired from competitive sailing to set up the Ellen MacArthur Foundation, a charity that works with business and education to accelerate the transition to a circular economy. A circular economy would create less waste as things should be designed to last a long time and be easy to maintain, repair, reuse or recycle.

Figure 2.2: Ellen MacArthur celebrates after completing her record solo round the world journey on 7 February 2005 in Falmouth, England

Discussion questions

1. What were the speeds of the six journeys mentioned in the first paragraph? Assume that the Earth's circumference is 40 000 km
2. How could the fastest boat not win a round-the-world yacht race?

2.1 Understanding speed

Measuring speed

If you travel on a major highway or through a large city, the chances are that someone is watching you. Cameras by the side of the road and on overhead road signs keep an eye on traffic as it moves along. Some cameras are there to monitor the flow, so that traffic managers can take action when blockages develop, or when accidents occur. Other cameras are equipped with sensors to spot speeding motorists, or those who break the law at traffic lights. In some busy places, traffic police may observe the roads from helicopters.

In this chapter, we will look at ideas of motion and speed. In Chapter 3, we will look at how physicists came to understand the forces involved in motion, and how to control them to make our everyday travel possible.

Distance, time and speed

There is more than one way to determine the **speed** of a moving object. Several methods to determine speed rely on making two measurements:

- the total distance travelled between two points
- the total time taken to travel between these two points.

We can then work out the **average speed** between the two points.

[illegible]

$$\text{average speed} = \frac{\text{total distance travelled}}{\text{total time taken}}$$

KEY WORDS

speed: the distance travelled by an object per unit of time

average speed: the speed calculated from total distance travelled divided by total time taken

We can use the equation for speed in the definition when an object is travelling at a constant speed. If it travels 10 metres in 1 second, it will travel 20 metres in 2 seconds. Its speed is 10 m/s.

We cannot say whether it was travelling at a steady speed, or if its speed was changing. For example, you could use a stopwatch to time a friend cycling over a fixed distance, for example, 100 metres (see Figure 2.3). Dividing distance by time would tell you their average speed, but they might have been speeding up or slowing down along the way.

Table 2.1 shows the different units that may be used in calculations of speed. SI units are the standard units used in physics. The units m/s (metres per second) should remind you that you divide a distance (in metres, m) by a time (in seconds, s) to find speed. In practice, many other units are used. In US space programmes, heights above the Earth are often given in feet, while the spacecraft's speed is given in knots (nautical miles per hour). These awkward units did not prevent them from reaching the Moon!

Figure 2.3: Timing a cyclist over a fixed distance. Using a stopwatch involves making judgements as to when the cyclist passes the starting and finishing lines. This can introduce an error into the measurements. An automatic timing system might be better.

Quantity	SI unit	Other units
distance	metre, m	kilometre, km
time	second, s	hour, h
speed	metres per second, m/s	kilometres per hour, km/h

Table 2.1: Quantities, symbols and units in measurements of speed

A cyclist completed a 1500 metre stage of a race in 37.5 s. What was her average speed?

Step 1: Start by writing down what you know, and what you want to know.

distance = 1500 m

time = 37.5 s

speed = ?

Step 2: Now write down the equation.

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Step 3: Substitute the values of the quantities on the right-hand side.

$$\text{speed} = \frac{1500\text{ m}}{37.5\text{ s}}$$

Step 4: Calculate the answer.

speed = 40 m/s

Answer

The cyclist's average speed was 40 m/s.

Questions

1 a What was Usain Bolt's average speed when he achieved his 100 m world record of 9.58 s in 2009?

b How do you know that his top speed must have been higher than this?

2 A cheetah runs 100 m in 3.11 s. What is its speed?

3 Information about three trains travelling between stations is shown in Table 2.2.

Vehicle	Distance travelled / km	Time taken / minutes
train A	250	120
train B	72	50
train C	400	150

Table 2.2

a Which train has the highest average speed?

b Which train has the lowest average speed?

Determining speed in the laboratory

There are many experiments you can do in the laboratory if you can measure the speed of a moving trolley or toy car. Figure 2.4 shows how to do this using one or two light gates connected to an electronic timer (or to a computer). The light gate has a beam of (invisible) infrared radiation.

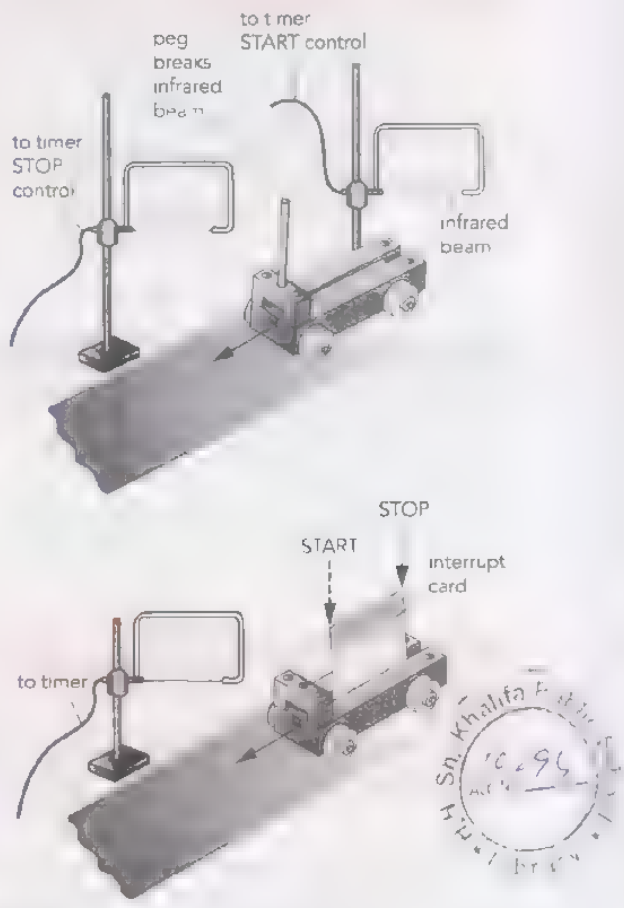


Figure 2.4: Using light gates to measure the speed of a moving trolley in the laboratory.

In the first part of Figure 2.4, the peg attached to the trolley breaks the beam of one light gate to start the timer. It breaks the second beam to stop the timer. The timer then shows the time taken to travel the distance between the two light gates.

In the second part of Figure 2.4, a piece of card, called an **interrupt card**, is mounted on the trolley. As the trolley passes through the gate, the leading edge of the interrupt card breaks the beam to start the timer. When the trailing edge passes the gate, the beam is no longer broken and the timer stops. The faster the trolley is moving, the shorter the time for which the beam is broken. Given the length of the interrupt card, the trolley's speed can be calculated.

light gates: allow the speed of an object passing between them to be calculated electronically

interrupt card allows the speed of an object passing through a light gate to be calculated; a timer starts when the card breaks the beam and stops when the beam is no longer broken

Rearranging the equation

It is better to remember one version of an equation and how to rearrange it than to try to remember three different versions. The equation

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

allows us to calculate speed from measurements of distance and time. This equation can also be written in symbols

$$v = \frac{s}{t}$$

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$v = \frac{s}{t}$$

This is sometimes known as the instantaneous speed, which is the speed at a particular instant or moment in time, whereas average speed is worked out over a longer time interval. Beware, s in this equation means distance (or displacement) and not speed. We can rearrange the equation to allow us to calculate distance or time.

For example, a railway signaller might know how fast a train is moving, and needs to be able to predict where it will have reached after a certain length of time:

$$\text{distance} = \text{speed} \times \text{time} \quad \text{or} \quad s = vt$$

Similarly, the crew of an aircraft might want to know how long it will take for their aircraft to travel between two points on its flight path:

$$\text{time} = \frac{\text{distance}}{\text{speed}} \quad \text{or} \quad t = \frac{s}{v}$$

A spacecraft is orbiting the Earth at a steady speed of 8.0 km/s (see Figure 2.5). How long will it take to complete a single orbit, a distance of 44 000 km?

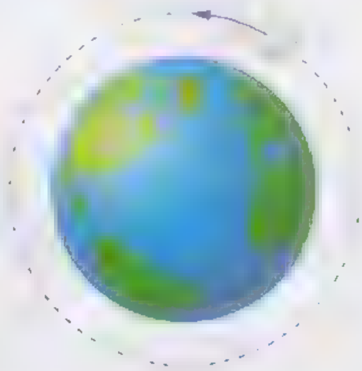


Figure 2.5

Step 1: Start by writing down what you know, and what you want to know.

speed (v) = 8.0 km/s

distance (s) = 40 000 km

time (t) = ?

Step 2: Choose the appropriate equation, with the unknown quantity, time, as the subject (on the left-hand side).

$$t = \frac{s}{v}$$

Step 3: Substitute values – it can help to include units.

$$t = \frac{40000\ \text{km}}{8.0\ \text{km/s}}$$

Step 4: Perform the calculation.

t = 5000 s

Answer

The time to complete a single orbit (44 000 km) is 5500 s. This is about 92 minutes (5500 − 60 = 91.667). So, the spacecraft takes 92 minutes to orbit the Earth once.

Worked Example 2.2 illustrates the importance of looking at the units. Because speed is in km/s and distance is in km, we do not need to convert to m/s and metres. We would get the same answer if we did the conversion:

$$\text{time} = \frac{40\,000\,000\ \text{m}}{8000\ \text{m/s}}$$

$$= 5000\ \text{s}$$

Questions

4 An aircraft travels 900 metres in 3.0 seconds. What is its speed?

5 A car travels 400 km in 3.5 hours. What is the speed of the car in km/h and m/s?

6 The Voyager spacecraft is moving at 17 000 m/s. How far will it travel in one year? Give your answer in km.

7 Calculate how many minutes it takes sunlight to reach us from the Sun. Light travels at 3×10^8 m/s and the Sun is about 144 million km away.

8 A cheetah can maintain its top speed of 31 m/s over a distance of 100 metres while some breeds of gazelle, such as Thomson's gazelle, have a top speed of 25 m/s. This question considers how close the cheetah needs to be to catch the gazelle if they have both just reached top speed.

- **a** How long does it take a cheetah to cover 100 m?
- **b** What is the closing speed of the cheetah, that is, what is the difference in speed between the cheetah and the gazelle?
- **c** How far ahead of the cheetah would the gazelle need to be to escape? (Hint: you need the time you calculated in **a** and the closing speed you calculated in **b**.)
- **d** How long would it take the cheetah to catch the gazelle with the closing speed you calculated in **b** and the distance apart you calculated in **c**?

ACTIVITY 2.1

Running with the wind behind you

In 2011, Justin Gatlin ran 100 metres in 9.45 seconds (faster than Usain Bolt's world record by 0.13 seconds). However, he was pushed along by a 20 m/s tailwind generated by giant fans as part of a Japanese game show. A 100 m or 200 m sprint record can stand only if a tail wind does not exceed 2 m/s. Why does this rule not apply to longer events?

First, think about how you might approach this problem.

The day Roger Bannister ran a mile in four minutes (6 May 1954) he almost decided not to race because it was too windy. Imagine there is a tailwind along the final straight section of a 400 m track which speeds you up, and a headwind on the opposite straight section which slows you down. Why do the effects of the tailwind and headwind **not** cancel out? (Hint: you need to think about the time it would take you to run the straight sections.)

1 Imagine that you are a 400 m runner who can run the distance in 40 s (a new world record) at the same average speed of 10 m/s. Assume that the 400 m track is equally divided so that the straight sections and bends are each 100 m long.

Plot your time for the 400 m (y-axis) against wind speed (x-axis). When you are running against the wind on the straight section opposite the finish line, subtract the wind speed from your normal running speed. When you are running with the wind on the final straight section before the finish line, add the wind speed to your normal running speed.

For example, if there is a wind speed of 1 m/s, your speed along the straight opposite the finish line will be 9 m/s while it will be 11 m/s along the straight section before the finish line. Then you need to add the times for each straight section to the 20 s for the bends. Repeat this, increasing the wind speed by 1 m/s each time, until you reach 10 m/s.

2 Could you have reached the answer without plotting a graph?

3 Discuss whether it is realistic to add or subtract the wind speed to your normal running speed.

4 Design an experiment to test how wind speed affects running speed. You might need to include equipment that you do not have access to (such as the giant fans used on the Japanese game show).

Discuss your answers to the activity with the person sitting next to you. Have they thought of anything you haven't included in your answer? Would you add anything to your answers after your discussion?

2.2 Distance–time graphs

You can describe how something moves in words. 'The coach drove away from the bus stop. It travelled at a steady speed along the main road, leaving town. After five minutes, it reached the highway, where it was able to speed up. After ten minutes, it was forced to stop because of traffic.'

We can show the same information in the form of a distance–time graph, as shown in Figure 2.6a. This graph is in three sections, corresponding to the three sections of the coach's journey.

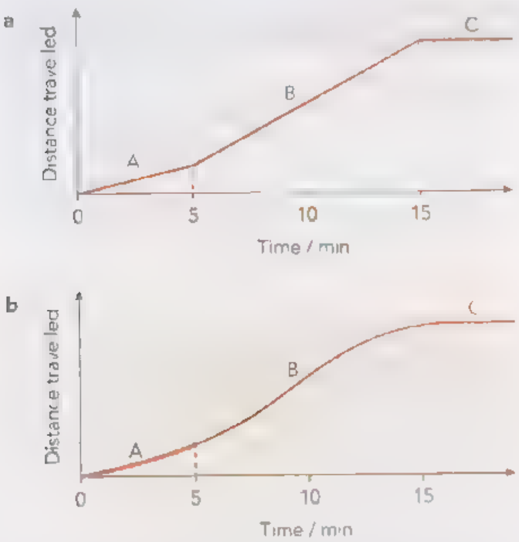


Figure 2.6 a and b: A graph to represent the motion of a coach as described in the text. The slope of the graph tells us about the coach's speed.

In section A, the graph slopes up gently, showing that the coach was travelling at a slow speed.

In section B, the graph becomes steeper. The distance of the coach from its starting point is increasing more rapidly. It is moving faster.

In section C, the graph is flat (horizontal). The distance of the coach from its starting point is not changing. It is stationary.

The slope of the distance–time graph tells us how fast the coach is moving. The steeper the graph, the faster it is moving (the greater its speed). When the graph becomes horizontal, its slope is zero. This tells us that the coach's speed is zero in section C. It is not moving.

Figure 2.6a shows abrupt (instant) changes in speed between A, B and C. It would not be a very comfortable ride for the passengers! Instead of abrupt changes in speed, the speed would change more slowly in the real world and there would be smooth curves joining the sections (Figure 2.6b). The increasing gradient of the upward-sloping curve between A and B would show that the coach was speeding up (accelerating) and the decreasing gradient of the curve between B and C would show that the coach was slowing down (decelerating). However, we will only look at graphs with angled edges as in Figure 2.6a.

Questions

9 A car pulled away from the lights and travelled at a steady speed along an empty road. After 8 minutes it joined a main road, where it travelled at about twice the original speed for 12 minutes. The car then met a traffic jam and had to quickly slow down and stop. The traffic cleared after 5 minutes but then the car travelled slowly, at about half the original speed.

Sketch a distance–time graph to show the car's journey.

10 Figure 2.7 shows the distance–time graph for a woman running a mountain marathon.

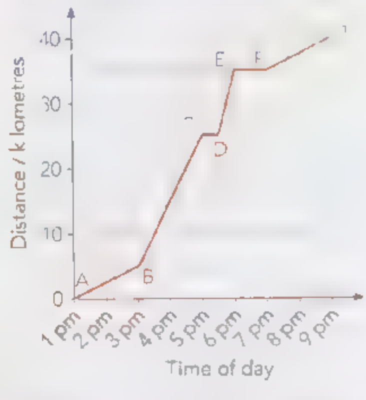


Figure 2.7: Distance–time graph

a How far did she travel?
b What was her average speed in km/h?
c How many stops did she make?
d The rules said she had to stop for half an hour for food. When did she take her break?
e Later she stopped to help an injured runner. When did this happen?
f What would her average speed have been if she had not stopped at all?
g What was her highest speed and over what section did this happen?

Express trains, slow buses

An express train is capable of reaching high speeds, perhaps more than 300 km/h. However, when it sets off on its journey, it may take several minutes to reach this top speed. Then it takes a long time to slow down when it approaches its destination. The French TGV trains (Figure 2.8) run on lines that are reserved solely for their operation, so that their high-speed journeys are not disrupted by slower, local trains.

A bus journey is full of accelerations and decelerations. The bus accelerates away from the stop. Ideally, the driver hopes to travel at a steady speed until the next stop. A steady speed means that you can sit comfortably in your seat. Then there is a rapid deceleration as the bus slows to a halt. A lot of accelerating and decelerating means that you are likely to be thrown about as the bus changes speed. The gentle acceleration of an express train will barely disturb the drink in your cup. The bus's rapid accelerations and decelerations would make it impossible to avoid spilling the drink (Figure 2.9).

Figure 2.8: France's high-speed trains, the TGVs (Trains à Grande Vitesse), run on dedicated tracks. Their speed has made it possible to travel 600 km from Marseille in the south to Paris in the north, attend a meeting, and return home again within a single day

Figure 2.9: It can be uncomfortable on a packed bus as it accelerates and decelerates along its journey

2.3 Understanding acceleration

Some cars, particularly high performance ones, are advertised according to how rapidly they can accelerate. An advert may claim that a car goes 'from 0 to 100 km/h in 5 s'. This means that, if the car accelerates at a steady rate, it reaches 20 km/h after 1 s, 40 km/h after 2 s, and so on. We could say that it speeds up by 20 km/h every second. In other words, its acceleration is 20 km/h per second.

So, we say that an object accelerates if its speed increases. Its **acceleration** tells us the rate at which its speed is changing, that is, the change in speed per unit time.

When an object slows down, its speed is also changing. We say that it is decelerating. Instead of an acceleration, it has a deceleration.

Speed and velocity, vectors and scalars

In physics, the words 'speed' and 'velocity' have different meanings, although they are closely related: **velocity** is an object's speed in a particular stated direction. So, we could say that an aircraft has a speed of 200 m/s but a velocity of 200 m/s due north. We must give the direction of the velocity or the information is incomplete.

Velocity is an example of a **vector quantity**. Vectors have both magnitude (size) and direction. Another example of a vector is weight – your weight is a force that acts downwards, towards the centre of the Earth.

Speed is an example of a **scalar quantity**. Scalars only have magnitude. Temperature is an example of another scalar quantity.

You will learn more about vectors and scalars in Chapter 3.

acceleration: the rate of change of an object's velocity

velocity: the speed of an object in a stated direction

vector quantity: has both magnitude (size) and direction

scalar quantity: is something that has magnitude but no direction

Speed–time graphs

Just as we can represent the motion of a moving object by a distance–time graph, we can also represent it by a speed–time graph. A speed–time graph shows how the object's speed changes as it moves. Always check any graph by looking at the axes to see the labels.
A speed–time graph has speed on the vertical axis and time on the horizontal axis.

Figure 2.10 shows a speed–time graph for a bus. The graph frequently drops to zero because the bus stops to let people on and off. Then the line slopes up, as the bus accelerates away from the stop. Towards the end of its journey, the bus is moving at a steady speed (horizontal graph), as it does not have to stop. Finally, the graph slopes downwards to zero again as the bus pulls into the terminus and stops.

The slope of the speed–time graph tells us about the bus's acceleration:

- the steeper the slope, the greater the acceleration
- a negative slope means a deceleration (slowing down)
- a horizontal graph (slope = 0) means a constant speed.

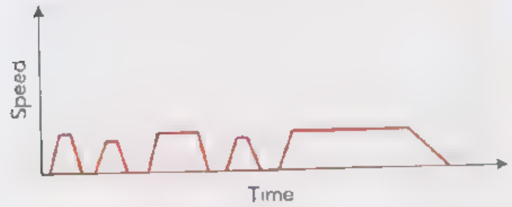


Figure 2.10: A speed–time graph for a bus on a busy route. At first, it has to halt frequently at bus stops. Towards the end of its journey, it maintains a steady speed.

Graphs of different shapes

Speed–time graphs can show us a lot about an object's movement. Was it moving at a steady speed, or speeding up, or slowing down? Was it moving at all?

Figure 2.11 represents a train journey. The graph is in four sections. Each section illustrates a different point:

- A: sloping upwards, so the speed increases and the train is accelerating
- B: horizontal, so the speed is constant and the train is travelling at a steady speed
- C: sloping downwards, so the speed decreases and the train is decelerating
- D: horizontal, so the speed has decreased to zero and the train is stationary.

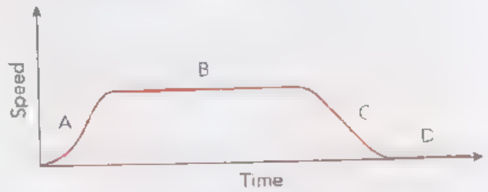


Figure 2.11: An example of a speed–time graph for a train during part of its journey

The fact that the graph lines are curved in sections A and C tells us that the train's acceleration was changing. If its speed had changed at a steady rate, these lines would have been straight.

Questions

11 Two students live in the same apartment block in Hometown and attend the same school in Schooltown, as shown in Figure 2.12. For this question, work in km and hours.

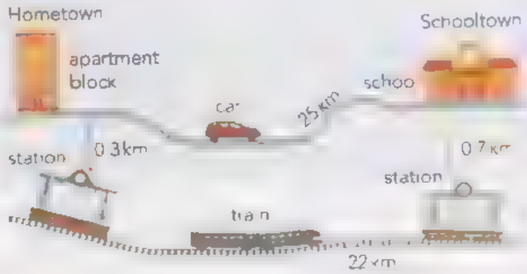


Figure 2.12

a Arun gets a lift to school in his mother's car. The traffic is heavy so the average speed for the journey is 40 km/h. How many minutes does it take Arun to get to school?

b Sofia leaves home at the same time as Arun but she walks the 0.3 km to Hometown station, waits 3 minutes (0.05 hour) for the train, travels on the train to Schooltown station (journey distance 22 km) and walks the 0.7 km from Schooltown station to the school. The train averages 88 km/h and Sofia walks at 5 km/h. How many minutes does it take Sofia to get to school?

c How many minutes shorter is Sofia's journey time than Arun's?

d Draw a speed–time graph for their journeys on the same axes but assume that any change in speed is instant (do not show the acceleration)

12 Look at the speed–time graph in Figure 2 13.

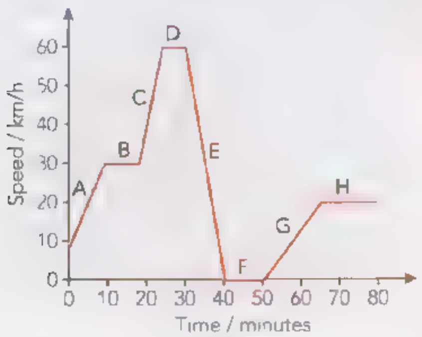


Figure 2.13

Name the sections that represent:

a steady speed

b speeding up (accelerating)

c being stationary

d slowing down (decelerating).

13 A car is travelling at 20 m/s. The driver sees a hazard. After a reaction time of 0.7 s, she performs an emergency stop by applying the brakes. The car takes a further 3.3 s to come to a stop. Sketch a speed–time graph for her journey from the moment she sees the hazard to the moment she brings her car to a stop. Label the graph with as many details as you can.

14 a Copy Table 2.3 and sketch the motion graphs for each motion described.

Motion of body	Distance–time graph	Speed–time graph
at rest		
moving at constant speed		
constant acceleration (speeding up)		
constant deceleration (slowing down)		

Table 2.3

b Copy Table 2.4 and sketch the speed–time graphs for each acceleration described.

Motion of body	constant acceleration	increasing acceleration	decreasing accleration
accelerating			
decelerating			

Table 2.4

Finding distance travelled

A speed–time graph represents an object's movement It tells us about how its speed changes. We can also use the graph to deduce (work out) how far the object travels. To do this, we have to make use of the equation:

distance = area under speed–time graph

The area under any straight-line graph can be broken down into rectangles and triangles. Then you can calculate the area using:

area of rectangle = width × height

area of a triangle = $\frac{1}{2}$ × base × height

To understand this equation, consider Worked Examples 2.3, 2 4 and 2.5.

Calculate the distance you travel when you cycle for 20 s at a constant speed of 10 m/s (see Figure 2.14).

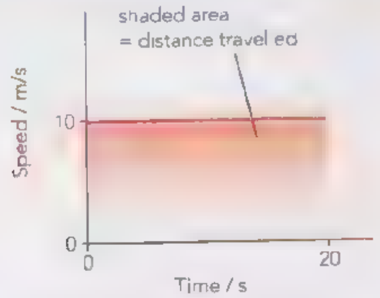


Figure 2.14: Speed–time graph for Worked Example 2.3

Step 1: Distance travelled is the same as the shaded area under the graph. This rectangle is 20 s wide and 10 m/s high, so its area is 10 m/s × 20 s = 200 m.

Step 2: Check using the equation:

distance travelled = speed × time
= 10 m/s × 20 s = 200 m

Answer

You would travel 200 metres.

You set off down a steep ski slope. Your initial speed is 0 m/s. After 10 s you are travelling at 30 m/s (see Figure 2.15). Calculate the distance you travel in this time.

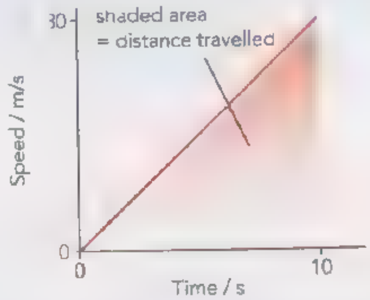


Figure 2.15: Speed–time graph for Worked Example 2.4

Step 1: Distance travelled is the same as the shaded area under the graph. The shape is a triangle with a height of 30 m/s and base of 10 s.

$$\text{area of a triangle} = \frac{1}{2} \times \text{base} \times \text{height}$$
$$\frac{1}{2} \times 10\,\text{s} \times 30\,\text{m/s}$$
$$= 150\,\text{m}$$

Step 2: Check using the equation:

$$\text{average speed} = \frac{\text{initial velocity} + \text{final velocity}}{2}$$
$$= \frac{0\,\text{m/s} + 30\,\text{m/s}}{2}$$
$$= 15\,\text{m/s}$$

$$\text{distance travelled} = \text{average speed} \times \text{time}$$
$$= 15\,\text{m/s} \times 10\,\text{s}$$
$$= 150\,\text{m}$$

Answer

You travel 150 metres.

A train's motion is represented by the graph in Figure 2.16. Calculate the distance the train travels in 60 s.

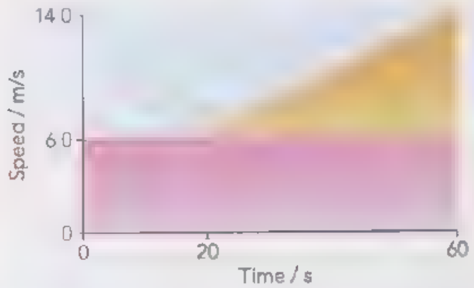


Figure 2.16: Speed–time graph for Worked Example 2.5.

Step 1: Distance travelled is the same as the shaded areas under the graph. This graph has two shaded areas: the pink rectangle and the orange triangle.

Step 2: Find the area of the pink rectangle.

It is 60 s wide and 6.0 m/s high, so its area = 60 s × 6.0 m/s = 360 m

(Note, this tells us how far the train would have travelled if it had maintained a constant speed of 6.0 m/s.)

Step 3: Find the area of the orange triangle. It has a base of 40 s and height of 14.0 m/s − 6.0 m/s = 8.0 m/s

area of a triangle $= \frac{1}{2} \times$ base $\times$ height

$= \frac{1}{2} \times 40\,\text{s} \times 8.0\,\text{m/s}$

$= 160\,\text{m}$

(Note: this tells us the extra distance travelled by the train because it was accelerating.)

Step 4: Add these two areas to find the total area and, therefore, the total distance travelled:

total distance travelled = 360 m + 160 m

= 520 m

Step 5: Check using the equation

distance travelled = average speed × time

The train travelled for 20 s at a steady speed of 6.0 m/s, and then for 40 s at an average speed of 10.0 m/s. So:

distance travelled = (6.0 m/s × 20 s) + (10.0 m/s × 40 s)

= 120 m × 400 m

= 520 m

Answer

In 60 s, the train travelled 520 metres.

Question

15 **a** Draw a speed–time graph to show a car that accelerates uniformly from 6 m/s for 5 s then travels at a steady speed of 12 m/s for 5 s.

b On your graph, shade the area that shows the distance travelled by the car in 10 s.

c Calculate the distance travelled in this time.

The 4 × 100 metre relay

The purpose of this activity is to apply what you have learned about motion (and particularly sketching speed–time graphs) to a real problem. If you get the chance to take this activity out onto a running track, you will need to take time and distance measurements (something you learned about in Chapter 1).

Success in a 4 × 100 m relay race depends both on the speed of the runners and effective baton exchange between the runners. The baton must pass between runners within a 30 m changeover (or passing) zone, which includes a 10 m acceleration (or fly) zone. Figure 2.17 shows the first of these three passing zones.

CONTINUED

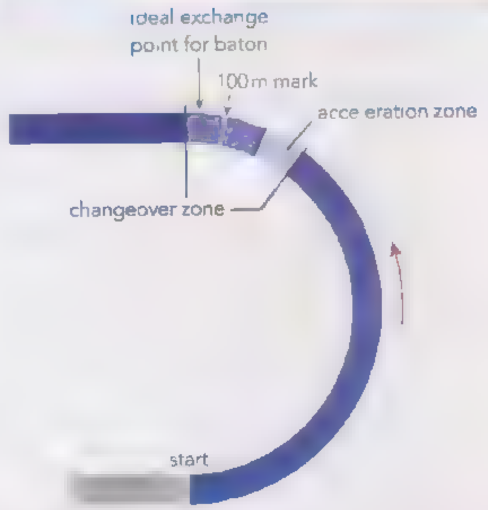


Figure 2.17: The first bend of a 400m athletics track.

Each athlete actually sprints for more than 100 m, as shown in Table 2.5. By planning for the baton to exchange between runners at the beginning or end of the changeover box, you can adjust the distance each runner runs. You might have a slightly shorter distance for a 60 m sprinter and a lengthened distance for a 100 m runner who also runs 200 m, which also makes them used to running bends. Usually, each runner keeps the baton in the same hand and passes it to the opposite hand of the next runner to exchange the baton. Usually, the first runner carries the baton in their right hand.

1 In what hand will runners receive and carry the baton on subsequent legs?

2 What are the advantages of passing the baton to the opposite hand?

Ideally, during the baton exchange the speeds of the runners should be the same. To achieve this the outgoing runner starts his run when the incoming runner reaches a check mark.

3 How would you work out where to place the check mark? (Hint: it might help if you sketch speed–time graphs on the same axes for both runners, starting when the runner receiving the baton starts running.) What other information would you need to make this accurate?

4 Even at Olympic finals teams can be disqualified (stopped from taking part) if they drop the baton or pass it outside of the changeover zone. Why does this happen so often?

5 Imagine you are the school's athletics coach. Table 2.5 lists the times for runners who often compete in the senior 4 × 100 m relay.

Use this information to select your team and decide which leg each runner should run and enter their names on the team sheet. Do you have a strategy for deciding which athlete runs which leg? What other information might you want to gather before making a decision? For example, Sajan suggests that he is the best starter. Some athletes are better at running bends. Some are better at passing or receiving the baton.

Athlete name	100 m personal best / s	200 m personal best / s	Right-handed, left-handed, or ambidextrous (happy using either hand)	Good bend runner
Sajjan Sidhu	12.1	25.8	right	prefers bends
Gar Ps Ho	11.8	24.3	right, ambidextrous	prefers bends
Andrew Kerr-Chin	11.1	24.4	ambidextrous	prefers straights but good at both
Tom Schofield	11.7	25.1	right, ambidextrous	better at straights
Oliver Hudson	12.6	26.3	ambidextrous	happy to run bends

Table 2.5

CONTINUED

6 Collect data from your own group. Use this to select a 4 × 100 m team and decide who should run each leg. Copy and complete this team sheet.

Team sheet			
Leg	Typical distance actually run / m	Athlete name	100 m personal best
1	105		
2	125		
3	125		
4	120		

Table 2.6

SELF-ASSESSMENT

In science it is often helpful to visualise tasks. For question 3, did you have a clear idea of how to work out where to place the check marks? Did the idea of sketching the speed–time graphs for the runners help? (The difference in the area under the two graphs up to the moment of baton exchange should tell you how far in front of the acceleration zone to place the check mark).

What other information did you need before deciding which runner should run each leg?

2.4 Calculating speed and acceleration

From a distance–time graph, we can find how fast something is moving. Figure 2.18 shows information about a car journey between two cities. The car travelled more slowly at some times than at others. It is easier to see this if we present the information as a graph.

From the graph, you can see that the car travelled slowly at the start of its journey, and also at the end, when it was travelling through the city. The graph is steeper in the middle section, when it was travelling on the open road between the cities.

The graph also shows how to use the gradient to calculate the car's speed on the open road:

speed = gradient of distance–time graph

More detail is given in Worked Example 2.6.

Use the gradient of the graph in Figure 2.18 to calculate the car's speed on the open road.

Distance travelled / km	Time taken / h
0	0.0
10	0.4
20	0.8
100	1.8
110	2.3

Table 2.7: Data for a car journey

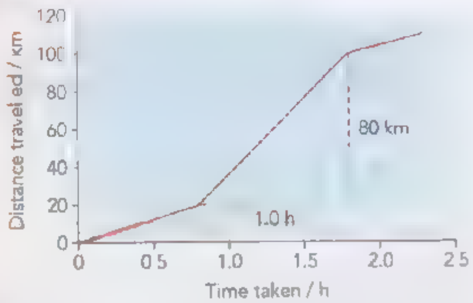


Figure 2.18: Distance–time graph for a car journey

speed = gradient of distance–time graph

Step 1: Identify the relevant straight section of the graph. Here, we are looking at the straight section in the middle of the graph, where the car's speed was constant.

Step 2: Draw horizontal and vertical lines to complete a right-angled triangle.

Step 3: Calculate the lengths of the sides of the triangle.

Step 4: Divide the vertical height by the horizontal width of the triangle ('up divided by along').

vertical height = 80 km

horizontal width = 1.0 h

$$\text{gradient} = \frac{80\text{ km}}{1.0\text{ h}}$$

$$= 80\text{ km/h}$$

Answer

The car's speed was 80 km/h for this section of its journey.

Note: It helps to include units in the calculation because then the answer will automatically have the correct units, in this case, km/h.

Question

16 Table 2.8 shows information about a train journey.

Station	Distance travelled / km	Time taken / minutes
Hornby	0	0
Kirby Lonsdale	10	30
Ingleton	20	45
Dolphinholme	46	60
Galgate	56	80

Table 2.8

Use the data in Table 2.8 to plot a distance–time graph for the train. Find the train's average speed between Kirby Lonsdale and Dolphinholme. Give your answer in km/h.

Calculating acceleration

Picture an express train setting off from a station on a long, straight track. It may take 300 s to reach a velocity of 300 km/h along the track. Its velocity has increased by 1 km/h each second, and so we say that its acceleration is 1 km/h per second.

These are not very convenient units, although they may help to make it clear what is happening when we talk about acceleration. To calculate an object's acceleration we need to know two things:

- its change in velocity (how much it speeds up)
- the time taken (how long it takes to speed up).

The acceleration of the object is defined as the change in an object's velocity per unit time.

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}}$$

We can write the equation for acceleration in symbols with Δv for change in velocity and Δt for time taken. So we can write the equation for acceleration like this:

$$a = \frac{\Delta v}{\Delta t}$$

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}}$$

$$a = \frac{\Delta v}{\Delta t}$$

Alternatively, because there are two velocities, we could use two symbols: u = initial velocity and v = final velocity. Now we can write the equation for acceleration like this:

$$a = \frac{v - u}{\Delta t}$$

The advantage of this equation is that if the final velocity is less than the initial velocity, the answer is negative. This tells you that the acceleration is negative (i.e. that the object is decelerating).

In the example of the express train, we have initial velocity u = 0 km/h, final velocity v = 300 km/h and time taken t = 300 s.

So, acceleration $a = \frac{300\text{ km/h} - 0\text{ km/h}}{300\text{ s}}$ = 1 km/h per second. Worked Example 2.7 uses the more standard velocity units of m/s.

Units of acceleration

In Worked Example 2.7, the units of acceleration are given as m/s^2 (metres per second squared). These are the standard units of acceleration. The calculation shows that the aircraft's velocity increased by 2 m/s every second, or by 2 metres per second per second. It is simplest to write this as 2 m/s^2, but you may prefer to think of it as 2 m/s per second, as this emphasises the meaning of acceleration.

[illegible]

An aircraft accelerates from 100 m/s to 300 m/s in 100 s. What is its acceleration?

Step 1: Start by writing down what you know, and what you want to know.

initial velocity u = 100 m/s

final velocity v = 300 m/s

time t = 100 s

acceleration a = ?

Step 2: Now calculate the change in velocity.

change in velocity = 300 m/s − 100 m/s = 200 m/s

Step 3: Substitute into the equation.

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}} = \frac{200\ \text{m/s}}{100\ \text{s}} = 2.0\ \text{m/s}^2$$

Alternatively, you could substitute the values of u, v and t directly into the equation

[illegible]

Answer

The aircraft's acceleration is 2.0 m/s^2.

If you are working out the acceleration of an object that is slowing down, then this alternative method shown in Worked Example 2.7 will give a negative answer. If the aircraft was slowing down from 300 m/s to 100 m/s then its acceleration would be

$$a = \frac{v - u}{t} = \frac{100\ \text{m/s} - 300\ \text{m/s}}{100\ \text{s}} = -2\ \text{m/s}^2$$

This is because acceleration is a vector quantity: it has a direction. It can be forwards (positive) or backwards (negative). So it is important always to think about velocity rather than speed when working out accelerations, because velocity is also a vector quantity.

Questions

17 Which of the following could not be a unit of acceleration?

km/s^2 mph/s km/s m/s^2

18 A car sets off from traffic lights. It reaches a speed of 21 m/s in 10 s. What is its acceleration?

19 A train, initially moving at 15 m/s, speeds up to 39 m/s in 120 s. What is its acceleration?

20 The speed of a car increases from 12 m/s to 20 m/s in 4 seconds.

- **a** Sketch the speed–time graph.
- **b** Calculate the acceleration.
- **c** Use the graph to work out the distance covered in those 4 seconds.
- **d** Calculate the distance travelled.
- **e** If your answers to parts **c** and **d** are not the same, then work out where you have made a mistake.

Acceleration from speed–time graphs

A speed–time graph with a steep slope shows that the speed is changing rapidly – the acceleration is greater. It follows that we can find the acceleration of an object by calculating the gradient of its speed–time graph.

acceleration = gradient of speed–time graph

Three points should be noted:

- The object must be travelling in a straight line; its velocity is changing but its direction is not.
- If the speed–time graph is curved (rather than a straight line), the acceleration is changing.
- If the graph is sloping downwards, the object is decelerating. The gradient of the graph is negative. So a deceleration is a negative acceleration.

A train travels slowly as it climbs up a long hill. Then it speeds up as it travels down the other side. Table 2.9 shows how its speed changes. Draw a speed–time graph to show this data. Use the graph to calculate the train's acceleration during the second half of its journey.

Time / s	Speed / m/s
0	6.0
10	6.0
20	6.0
30	8.0
40	10.0
50	12.0
60	14.0

Table 2.9: Speed of a train

Before starting to draw the graph, it is worth looking at the data in the table. The values of speed are given at equal intervals of time (every 10 s). The speed is constant at first (6.0 m/s). Then it increases in equal steps (8.0, 10.0, and so on). In fact, we can see that the speed increases by 2.0 m/s every 10 s. This is enough to tell us that the train's acceleration is 0.2 m/s². However, we will follow through the detailed calculation to illustrate how to work out acceleration from a graph.

Step 1: Draw the speed–time graph using the data in Table 2.9; this is shown in Figure 2.19.

The initial horizontal section shows that the train's speed was constant (zero acceleration).

The sloping section shows that the train was then accelerating.

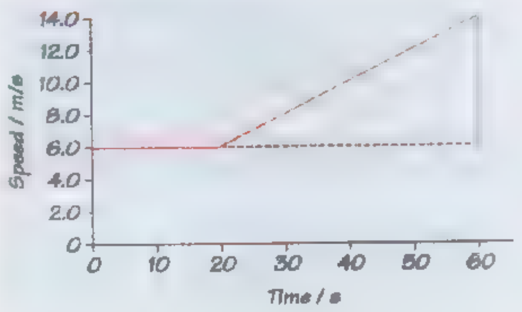


Figure 2.19: Speed–time graph for Worked Example 2.8

Step 2: Draw in a triangle to calculate the slope of the graph, as shown on Figure 2.19. This gives us the acceleration.

$$a = \frac{v - u}{\Delta t}$$

$$= \frac{14.0\,\text{m/s} - 6.0\,\text{m/s}}{60\,\text{s} - 20\,\text{s}}$$

$$= \frac{8.0\,\text{m/s}}{40\,\text{s}}$$

$$= 0.20\,\text{m/s}^2$$

Answer

The train's acceleration down the hill is 0.20 m/s².

Although Worked Example 2.8 uses the equation for acceleration, you are finding the gradient of the slope in Figure 2.19.

Figure 2.20 shows the speed–time graph for a skydiver from the moment she leaves an aircraft. She jumps from 5000 m and opens her parachute when she reaches 1500 m, 60 s after she jumps. You have already learned that you can find the acceleration from the gradient of a speed–time graph. However, there are places where the gradient of the graph is changing (when the graph is not a straight line). To find the acceleration at any moment in time, a tangent to the graph is drawn. This works for any graph, straight or curved.

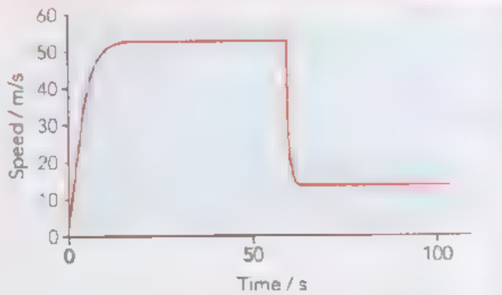


Figure 2.20: The speed–time graph for a skydiver, showing the first 105 s of the jump

Look at Figure 2.20. What is the skydiver's acceleration at:

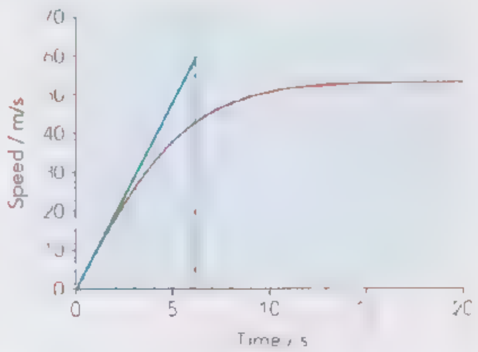
a 0 s

b 5.5 s?

Part a

Step 1: Draw a tangent to the graph at t = 0 s (shown below by the blue line).

Step 2: Draw in a triangle (shown below by the dashed lines).

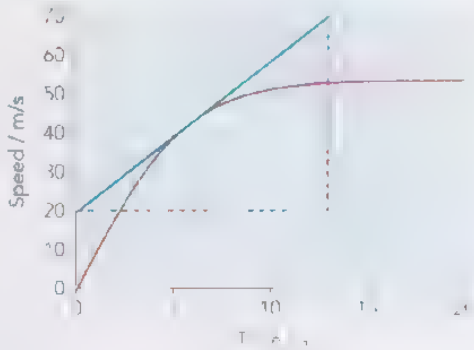


Step 3: Calculate the slope of the graph. This gives us the acceleration.

Part b

Step 1: Draw a tangent to the graph at t = 5.5 s (shown below by the blue line).

Step 2: Draw in a triangle to calculate the slope of the graph (shown below by the dashed lines).



Step 3: Calculate the slope of the graph. This gives us the acceleration.

Answer

The parachutist has the acceleration of free-fall (9.8 m/s²) the moment she jumps out of the aircraft (at t = 0 s) and her acceleration decreases with time until she reaches a constant speed. After 5.5 s her acceleration is 3.8 m/s².

Perhaps you can already explain why her acceleration changes as she falls but it will be explained in Chapter 3. Can you see when she opens her parachute in Figure 2.20? Recalling how to work out distance on a speed–time graph, can you work out how far she has fallen when she opens her parachute? Can you work out that she lands 160 s after she starts her jump?

Question

21 A car driver has to do an emergency stop. This is when the driver needs to stop the car in the shortest possible stopping distance. There is a delay between seeing a hazard and applying the brakes. This is due to the reaction time of the driver, sometimes called the thinking time. The distance the car moves in this time (when the car has not changed speed) is the thinking distance. The distance the car moves once the brakes are applied and until the car comes to a stop is the braking distance. The stopping distance = thinking distance + braking distance.

A car is travelling at 20 m/s when the driver sees a hazard. She has a reaction time of 0.7 s and brings her car to a stop 4.0 s after seeing the danger.

a Draw a speed–time graph to represent the car's motion during the 4.0 s described. Assume that the deceleration (negative acceleration) is constant.

b Use the graph to deduce (work out) the car's deceleration as it slows down.

c Use the graph to deduce how far the car travels during the 4.0 s described.

Using ticker tape to find the acceleration of a trolley down a ramp

You are going to investigate the motion of a trolley down a ramp. Some ticker tape is attached to the trolley – and a ticker timer marks the paper 50 times a second (Figure 2.21). As the trolley accelerates, the distance between the dots increases.

1. The ticker timer marks the paper 50 times a second. What interval of time does each gap represent?

   To find the speed at a particular dot, you need to measure the distance covered over a short interval of time centred on the dot. Measure the distance between the *preceding* (previous) dot and *succeeding* dot (the one that follows). For example, to find the speed at dot 15, we need to find the distance covered between dot 14 and dot 16 (13 mm) and then divide by the time taken to cover this distance ($2 \times 0.02\,s = 0.04\,s$), using the equation:

   $$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{13\,\text{mm}}{0.04\,\text{s}} = 0.325\,\text{m/s}$$

2. Copy and complete Table 2.10, using the ticker tape to help you

Dot number	Time since tape started / s	Distance covered / mm	Speed / m/s
0	0.0		
5	0.1		
10	0.2		
15		13	0.325
20			
25			
30			

Table 2.10

Figure 2.21: Ticker tape.

3. Plot a speed–time graph.
4. Use the gradient from the graph to calculate the acceleration

Alternative approach

Every fifth dot has been numbered. This corresponds to the distance travelled every 0.1 s.

1. Cut a copy of the the ticker tape into lengths corresponding to every fifth dot (0.1 s time interval).
2. Stick the lengths side by side (like a histogram) onto graph paper, with the bottom of each strip on the horizontal axis.
3. Draw a line through the dot at the top of each strip (or the middle of the top of each strip, if the dot is missing).
4. Work out the scale for each axis. The width of each strip is equal to a time interval of 0.1 s.
5. Work out the gradient of the speed–time graph you have constructed

PROJECT

Your teacher will decide whether you will work on your own, in pairs or as part of a small group. Your task is to plan a three-part revision lesson on the material in this chapter for the rest of your class, particularly the link between motion graphs and the equations of motion. Write down a plan to show what you would do and what resources you would use. If you have time, you can produce and teach the lesson to small groups of your classmates or the whole of your class. The following points will help you as you plan the revision lesson.

- You need to be able to answer questions on motion graphs and equations of motion so that you can then use them as a basis to write your own own questions.
- You need to produce model answers for your questions or come up with a better way of getting the ideas across.
- Insist that your classmates show their working.
- You need to label what parts of your questions are supplementary

Here are some suggested questions which you can use in your plan for the lesson:

Part 1: How to interpret motion graphs

Question for your classmates to answer: 'Copy and complete the table by stating what feature of the motion graph can be used to obtain the variable listed in the left-hand column. The first cell has been done for you.'

	Distance–time graph	Speed–time graph
distance	read off the vertical axis	
speed		
acceleration		

You might want to suggest that your classmates colour code the table in some way.

Can you think of a better way of getting information from motion graphs?

Part 2: Linking motion graphs to equations of motion

Question for your classmates to answer: 'A body moving at 2 m/s accelerates for 2 seconds until it reaches a speed of 4 m/s. Show that the body travels a distance of 6 m and accelerates at 1 m/s^2.'

You need your classmates to get the same answer for the question you produce using two different methods.

Method 1: Use the relevant equations (for acceleration and distance)

Some of your classmates will get the distance wrong because they do not use the average speed in the equation for distance.

Method 2: Sketch the motion graph

Your classmates should use the gradient of the graph to find the acceleration and the area under the curve to find the distance. However, some of your classmates will sketch the motion from the origin (instead of from 2 m/s) and will work out the area of a triangle (instead of a triangle plus a square) so will get a distance travelled of 2 metres. Others will measure the horizontal and vertical distances with a ruler to work out the gradient instead of using the scale on the axes to work out the changes in the speed and time to work out the gradient.

You need to come up with similar questions (different numbers) and their model answers. Perhaps try your question on a few of your friends to check that it is clear and to pick up common mistakes. You could provide your question and a wrong solution and ask other members of your class to spot and correct the mistakes.

Part 3: Putting learning into practice

Questions for your classmates to answer: Bloodhound LSR is being developed to achieve a new land speed record of 1000 mph. The vehicle will be timed over a 'measured mile' half way down a 12 mile long salt pan in South Africa

- If Bloodhound achieves 1000 mph, how long would it take to complete the 'measured mile'?

CONTINUED

Figure 2.22: Bloodhound LSR during a practice run on the Hakskeen pan in South Africa

- Sketch a speed–time graph for its journey. Label it with significant speeds and times. Assume that Bloodhound accelerates uniformly until it reaches the 'measured mile' and then decelerates uniformly so that it comes to rest 12 miles from the start (and before the end of the salt pan).
- What is the total time for the 12 mile journey?
- What is the acceleration or deceleration of the vehicle and how does this compare to the acceleration of freefall (9.81 m/s^2)?'

First, you need to answer the question yourself.

When you set your question, decide whether to convert the data in the question to SI units or get your classmates to do it themselves (1 mph = 0.447 m/s; 1 mile = 1610 m).

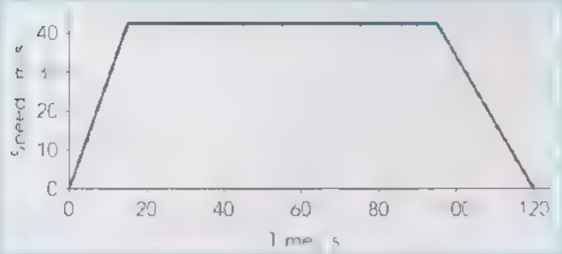
You could introduce the question with a short video clip about the vehicle. Adapt the questions above and produce a model answer so that your peers can check and correct their solutions. For example, you could flip the question by telling your peers the maximum acceleration and deceleration of the vehicle and get them to work out the minimum distance the 'track' needs to be, or you could change the data while keeping it realistic.

SUMMARY

Speed is distance divided by time.
Average speed is total distance divided by total time.
Light gates and interrupt cards can be used to measure speed in the laboratory.
The equation that relates speed, distance and time can be re-arranged to find any one of the variables, given the values of the other two.
The gradient (slope) of a distance–time graph represents speed
Acceleration is a change in speed.
The greater the gradient (slope) of a speed–time graph, the bigger the acceleration
Distance travelled can be calculated (worked out) from the area under a speed–time graph.
Speed can be calculated from the gradient of a distance–time graph and acceleration can be calculated from the gradient of a speed–time graph.
Speed is a scalar and velocity is a vector.
Acceleration can be calculated from the change of speed divided by time and a negative acceleration is the same as a deceleration.

EXAM-STYLE QUESTIONS

Use this graph for questions 1 and 2



1 How is a constant velocity shown on the graph? **[1]**

A the sloping line at the start
B the horizontal part of the line
C the area under the line
D the sloping line at the end

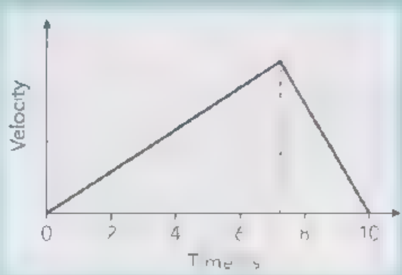
2 How is the distance travelled shown on the graph? **[1]**

A the sloping line at the start
B the horizontal part of the line
C the area under the line
D the sloping line at the end

3 A snail takes part in a snail race. The snail completes the 180 cm course in 7.0 minutes. What is the approximate average speed of the snail? **[1]**

A 0.43 m/s **B** 26 m/s **C** 0.26 m/s **D** 0.0043 m/s

4 The velocity–time graph shows the performance of a Formula 1* racing car as it accelerates from rest for 7.33 seconds and then brakes, coming to a stop in 2.69 seconds. It covers a distance of 520 metres.



What is the approximate maximum velocity of the car? **[1]**

A 50 m/s **B** 75 m/s **C** 105 m/s **D** 175 m/s

CONTINUED

5 The table shows Usain Bolt's split times from his world record 100 m run in Berlin in 2009. Each split time is for a 10 m section of the 100 m distance. The time for the first 10 m includes his reaction time of 0.146 s before he left his blocks.

Section / m	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Time / s	1.89	0.99	0.90	0.86	0.83	0.82	0.81	0.82	0.83	0.83

a Calculate the time that Usain Bolt takes to run the first 10 metres from the moment he starts moving. **[1]**

b Calculate Usain Bolt's average speed over the first 10 metres from the moment he starts moving. **[2]**

c Calculate Usain Bolt's maximum speed over the first 10 metres. Ignore his reaction time and assume his acceleration is constant. **[2]**

d Calculate Usain Bolt's acceleration over the first 10 metres. Ignore his reaction time and assume his acceleration is constant. **[2]**

e Calculate Usain Bolt's top speed in the race. Show your working. **[2]**

[Total: 8]

6 An aircraft happened to be flying near a volcano when it erupted. The co-pilot took some video footage. He handed the footage over to scientists for analysis. The scientists spotted a huge boulder that was moving at a constant speed horizontally (sideways) in the first frame and falling in subsequent frames of the video. They wanted to work out how far the ash and rock would spread.

a Plot a graph of the position of the boulder at intervals of 5 seconds. Plot the vertical height of the boulder (vertical axis) against the horizontal distance travelled (horizontal axis). **[3]**

Time / s	Horizontal distance travelled / m	Vertical height / m
0	0	4420
5	525	4292
10	1050	3924
15	1580	3311
20	2100	2453
25	2630	1349
30	3150	0

b Explain the shape of the graph. **[1]**

calculate: work out from given facts, figures or information

explain: set out purposes or reasons; make the relationships between things evident, provide why and/or how and support with relevant evidence

CONTINUED

c The scientists thought the aircraft had been at an altitude (height) of 4420 metres when the video was taken but it was at 3600 metres. Use your graph to estimate the (horizontal) distance the boulder will have travelled from the point that it was recorded on video to where it hit the ground. **[2]**

d Use your graph to estimate how long it took the boulder to hit the ground from where it was filmed. **[1]**

e Calculate the horizontal speed of the boulder. **[2]**

f Suggest why there is ash and rocks over a wide area and not just a circle of debris that your answer to c might suggest. **[1]**

[Total: 10]

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Work out speed from distance travelled and time taken	2.1			
Work out average speed from total distance travelled and total time taken.	2.1			
Describe experiments to measure speed in the laboratory	2.1			
Work out distance travelled from a speed–time graph.	2.3			
Find speed on a speed-time graph.	2.3			
Calculate acceleration from the change in velocity and time taken.	2.4			
Work out acceleration from a speed–time graph	2.4			
Explain the difference between speed and velocity	2.4			

› Chapter 3

Forces and motion

IN THIS CHAPTER YOU WILL:

- discover the differences between mass and weight
- describe the ways in which a resultant force may change the motion of a body
- find the resultant of two or more forces acting along the same line
- find out about the effect of friction (or air resistance or drag) on a moving object
- learn about circular motion
- learn how force, mass and acceleration are related
- [illegible] the conservation of momentum
- [illegible] vectors acting at right angles to each other

Look at the following questions Your teacher will give you some time to think about them on your own You may also take some time to discuss them with the person sitting next to you. Be prepared to share your answers with the class.

1 While sitting on your seat, describe any forces acting on you.

2 Imagine a ball thrown in the air Sketch the ball. Draw an arrow or arrows to show any forces acting on the ball and, if possible, label the arrows

3 Describe daily life without friction What do you think would change the most?

4 Look at Figure 3.1 and decide which path the Earth would follow if gravity stopped acting.

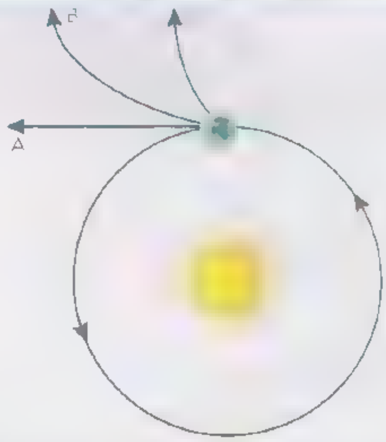


Figure 3.1: The Earth orbiting the Sun Which of the paths would Earth follow if the Sun suddenly stopped existing?

HYPERLOOP ONE

Transport systems would be much more efficient if less energy was wasted working against friction or air resistance. Hyperloop One promises to get rid of both. Elon Musk proposed it on 12 August 2013 as a faster alternative to air travel It combines two existing technologies maglev (magnetic levitation) and vactrain (vacuum tube train). Maglev trains use magnetic repulsion (like poles repel) to make the train float, which eliminates friction. A linear motor then accelerates the train: magnetic attraction (unlike poles attract) pulls the train from the front while magnetic repulsion pushes it from behind The trains will travel through tubes with most of the air removed using pumps. This will allow them to travel at Mach 7 that is seven times the speed of sound at sea level. This is about 2000 m/s much faster than supersonic aircraft In 2016, Hyperloop One launched its Hyperloop One Global Challenge and selected five countries for the development of the hyperloop networks US UK Canada Mexico, and India

Figure 3.2a: The idea of passengers travelling through a tube is not new. Passengers taking a ride in the first pneumatic passenger railway in the US erected at the Exhibition of the American Institute at the Amory, New York City, in 1867
b: A Hyperloop tube on display during the first test of the propulsion system at the Hyperloop One Test and Safety site on 11 May 2016 in Las Vegas, Nevada.

CONTINUED

Discussion questions

1 Describe the ways in which friction will be reduced in Hyperloop One

2 Describe any potential dangers of travelling in Hyperloop One

3.1 We have lift-off

It takes an enormous force to lift a giant space shuttle off its launch pad, and to propel it into space (Figure 3.3). The booster rockets that supply the initial thrust provide a force of several million newtons. As the spacecraft accelerates upwards, the crew experience the sensation of being pressed firmly back into their seats. That is how they know that their craft is accelerating.

Figure 3.3: A space shuttle accelerating away from its launch pad The force needed is provided by several rockets Once each rocket has used all its fuel, it will be jettisoned (dropped), to reduce the mass that is being carried up into space

Unbalanced forces change motion

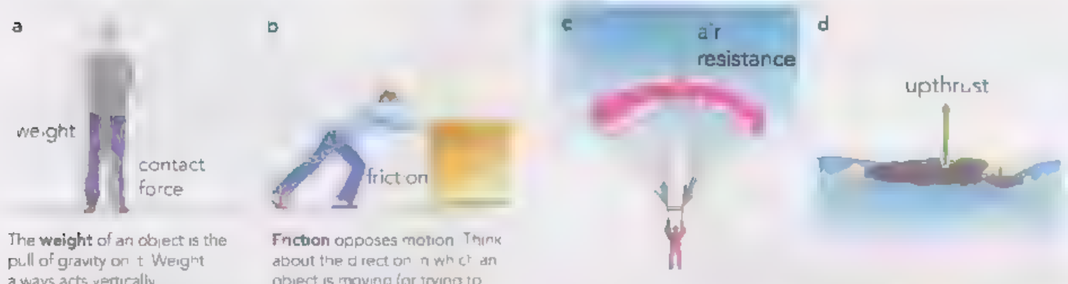
One moment, the shuttle is sitting on the ground, stationary. The next moment, it is accelerating upwards, pushed by the force provided by the rockets.

In this chapter, we will look at how **forces** – pushes and pulls – affect objects as they move. You will be familiar with the idea that the unit used for measuring forces is the **newton** (N). To give an idea of the sizes of various forces, here are some examples

- You lift an apple. The force needed to lift an apple is roughly one newton (1 N).
- You jump up in the air. Your leg muscles provide the force needed to do this, about 1000 N.
- You reach the motorway in your high-performance car, and press the accelerator pedal. The car accelerates forwards. The engine provides a force of about 5000 N
- You are crossing the Atlantic in a Boeing 747 jumbo jet. The four engines together provide a thrust of about 500 000 N. In total, that is about half the thrust provided by each of the space shuttle's booster rockets

Some important forces

Forces appear when two objects interact with each other Figure 3.4 shows some important forces. Each force is represented by an arrow to show its direction. Usually, the longer the arrow, the bigger the force is. Notice the convention that the arrow usually points away from the object of interest.



a: The **weight** of an object is the pull of gravity on it. Weight always acts vertically downwards. When two objects touch, there is a **contact force**. It is the contact force that stops you falling through the floor

b: **Friction** opposes motion. Think about the direction in which an object is moving (or trying to move). Friction acts in the opposite direction

c: **Air resistance** or **drag** is the force of friction when an object moves through air or water

d: **Upthrust** is the upward push of a liquid or gas on an object. The upthrust of water makes you float in the swimming pool

Figure 3.4: Some common forces

The car shown in Figure 3.5 is moving rapidly. The engine is providing a force to accelerate it forwards, but there is another force acting, which tends to slow down the car. This is air resistance, a form of friction caused when an object moves through the air. (Friction is also called drag, especially for motion through liquids.) The air drags on the object, producing a force that acts in the opposite direction to the object's motion.

Figure 3.5: A car moves through the air. Air resistance acts in the opposite direction to its motion.

A driver who needs to stop quickly will apply the brakes to take advantage of solid friction, when two surfaces make contact (the brake pads and brake discs, in this case). The kinetic energy of the car transfers into thermal energy, raising the temperature of the brakes. You can demonstrate this for yourself by rubbing your hands together. Energy transformations like these are discussed in more detail in Chapter 6. Solid friction exists even when the surfaces are not moving against each other, unless one or both surfaces are like ice and offer almost no resistance to motion (then they are said to have a very low coefficient of friction). Compare standing on concrete with standing on ice. There is much more solid friction on concrete and you do not have to think about keeping your balance. The solid friction between the sole of your shoes and concrete impedes motion (so reduces the possibility of slipping) and, because there is no motion of one surface against another, there is no increase in thermal energy. If you are running quickly on concrete and fall over you may notice that the graze on your knee feels hot. This is because your kinetic energy transfers into thermal energy due to the solid friction between your skin and concrete. A 'shooting star' is a meteor (lump of rock that burns up in our atmosphere). It shows that air resistance and drag lead to the transfer of kinetic energy to thermal energy.

force: the action of one body on a second body; unbalanced forces cause changes in speed, shape or direction

newton (N): the force required to give a mass of 1 kg an acceleration of 1 m/s^2

air resistance: friction acting on an object moving through air

friction: the force that acts when two surfaces rub over one another

drag: friction that acts on an object as it moves through a fluid (a liquid or a gas)

solid friction: the resistance to motion caused when two surfaces are in contact

Unbalanced forces produce acceleration

The car driver in Figure 3.6a is waiting for the traffic lights to change. When they go green, he moves forwards. The force provided by the engine causes the car to accelerate. In a few seconds, the car is moving quickly

along the road. The arrow in the diagram shows the force pushing the car forwards. If the driver wants to get away from the lights more quickly, he can press harder on the accelerator. The forward force is then bigger, and the car's acceleration will be greater

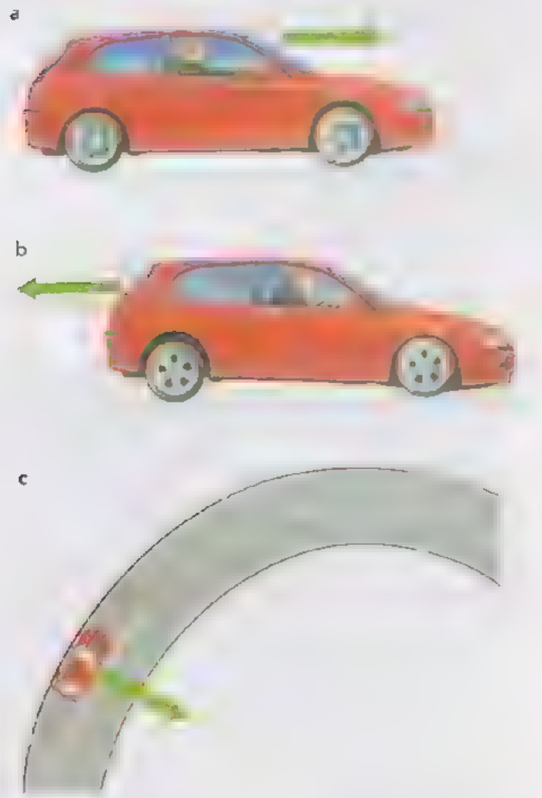


Figure 3.6: A force can be represented by an arrow. **a:** The forward force provided by the engine causes the car to accelerate forwards **b:** The backward force provided by the brakes causes the car to decelerate **c:** A sideways force causes the car to change direction

The driver reaches another junction, where he must stop. He applies the brakes. This provides another force to slow down the car (see Figure 3.6b). The car is moving forwards, but the force needed to make it decelerate is directed backwards. If the driver wants to stop in a hurry, a bigger force is needed. He must press hard on the brake pedal, and the car's deceleration will be greater.

Finally, the driver wants to turn a corner. He turns the steering wheel. This produces a sideways force on the car (Figure 3.6c), so that the car changes direction.

To summarise, we have seen several things about forces:

- They can be represented by arrows. A force has a direction, shown by the direction of the arrow.
- A force can make an object change speed. A forward force makes it speed up (accelerate), while a backward force makes it slow down (decelerate).
- A force can change the direction in which an object is moving

This can be summarised by saying that a body will remain at rest or will move at a constant speed in a straight line unless acted upon by a resultant force. There are alternative ways of saying the same thing. For example, a resultant force will change the speed or direction of a body. However, the problem with this statement is that some people forget to include starting and stopping as changes in speed. Another alternative is to say that a resultant force will change the velocity of a body, but as velocity is a vector, a resultant force can change the direction as well as the speed of a body. A resultant force can change both speed and direction at the same time

Question

1 **Figure 3.7 shows three objects that are moving. A force acts on each object. For each, say how its movement will change.**

Figure 3.7: Three moving objects.

Two or more forces along the same straight line

The two forces acting on the car in Figure 3.8a are:

- push of engine – 600 N to the right
- drag of air resistance – 400 N to the left

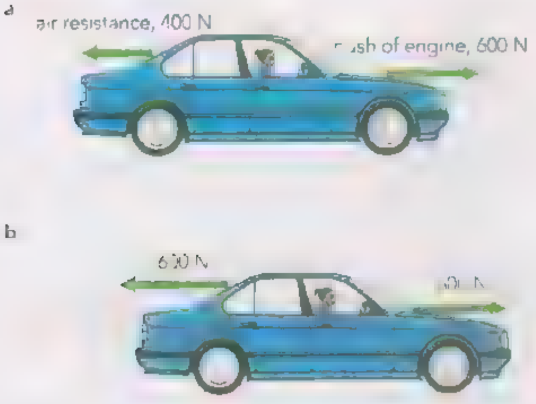


Figure 3.8: A car moves through the air. Air resistance acts in the opposite direction to its motion

We can work out the combined effect of these two forces by subtracting one from the other to give the resultant force acting on the car. The resultant force is the single force that has the same effect as two or more forces. So, in Figure 3.8a:

resultant force = 600 N − 400 N

= 200 N to the right

This resultant force will make the car accelerate to the right, but not as much as if there was no air resistance.

In Figure 3.8b, the car is moving even faster, and air resistance is greater. Now the two forces cancel each other out. So, in Figure 3.8b:

resultant force = 600 N − 600 N = 0 N

We say that the forces on the car are balanced. There is no resultant force and so the car no longer accelerates. It continues at a constant speed in a straight line.

- If no resultant force acts on an object, it will not accelerate; it will remain at rest or it will continue to move at a constant speed in a straight line.
- If an object is at rest or is moving at a constant speed in a straight line, we can say that there is no resultant force acting on it.

resultant force: the single force that has the same effect on a body as two or more forces

Question

2 The forces acting on three objects are shown in Figure 3.9

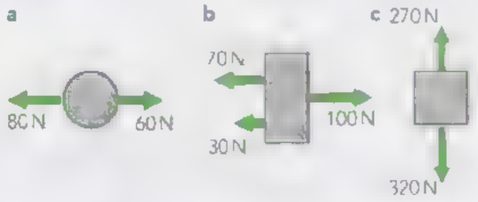


Figure 3.9: Forces acting on three objects.

For each of a, b and c

i state whether the forces are balanced or unbalanced

ii if the forces are unbalanced, calculate the resultant force on the object and give its direction

iii state how the object's motion will change

3.2 Mass, weight and gravity

If you drop an object, it falls to the ground. It is difficult to see how a falling object moves. However, a multi-flash photograph can show the pattern of movement when an object falls.

Figure 3.10 shows a ball falling. There are seven images of the ball, taken at equal intervals of time. The ball falls further in each successive time interval. This shows that its speed is increasing – it is accelerating.

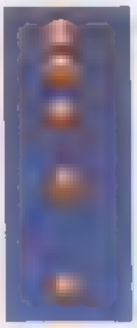


Figure 3.10: The increasing speed of a falling ball is captured in this multi-flash image

When an object accelerates, there must be a force that is causing it to do so. In this case, the force of **gravity** is pulling the ball downwards. The name given to the gravitational force acting on an object that has mass is its weight. Because weight is a force, it is measured in newtons (N).

Every object on or near the Earth's surface has weight. This is caused by the attraction of the Earth's gravity. The Earth pulls with a force of 10 N (approximately) on each kilogram of matter, so an object of mass 1 kg has a weight of about 10 N. Actually, the Earth pulls with a force of 9.8 N on each kilogram so an object of mass 1 kg has a weight of 9.8 N.

Because the Earth pulls with the same force on every kilogram of matter, every object falls with the same acceleration close to the Earth's surface. If you drop a 5 kg ball and a 1 kg ball at the same time, they will reach the ground at the same time.

The acceleration caused by the pull of the Earth's gravity is called the **acceleration of free fall** or the **acceleration due to gravity**. This quantity is given the symbol g and its value is approximately constant close to the surface of the Earth. It is approximately 9.8 m/s^2

Calculating weight and gravitational field strength

We have seen that an object of mass 1 kg has a weight of 9.8 N; an object of mass 2 kg has a weight of 19.6 N; and so on. To calculate an object's weight W from its mass m, we multiply by 9.8, the value of the acceleration of free fall g. We can write this as an equation in words and in symbols:

weight = mass × acceleration of free fall

$$W = mg$$

The **gravitational field strength** at a point is the gravitational force exerted per unit mass placed at that point. From the equation, $W = mg$, the gravitational field strength, g, is:

$$\text{gravitational field strength} = \frac{\text{weight}}{\text{mass}}$$

$$g = \frac{W}{m}$$

On the Earth's surface, the gravitational field strength is 9.8 N/kg. It has the same value as the acceleration of free fall or acceleration due to gravity that we met earlier and is often rounded up to 10 N/kg.

Distinguishing mass and weight

It is important to understand the difference between the two quantities, mass and weight.

- The mass of an object, measured in kilograms, tells you how much matter an object is composed of.
- The weight of an object, measured in newtons, is the gravitational force that acts on the object.

gravity: the force that exists between any two objects with mass

acceleration of free fall: the acceleration of an object falling freely under gravity

acceleration due to gravity: the acceleration of an object falling freely under gravity

gravitational field strength: the gravitational force exerted per unit mass placed at that point

If you take an object to the Moon, it will weigh less than it does on Earth, because the Moon's gravity is weaker than the Earth's. However, its mass will be unchanged, because the object is made of just as much matter as when it was on Earth.

When we weigh an object using a balance, we are comparing its weight with that of standard weights on the other side of the balance (Figure 3.11). We are making use of the fact that, if two objects weigh the same, their masses will be the same. We always talk about weighing an object. However, if the balance we use has a scale in kilograms or grams, we will find its mass, not its weight.

Figure 3.11: When the balance is balanced, we know that the weights on opposite sides are equal, and so the masses must also be equal

Questions

3 List the differences between mass and weight

4 A bag of sugar has a mass of 1 kg so its weight on Earth is 10 N. What can you say about the bag's mass and its weight if you take it:

  a to the Moon, where gravity is weaker than on Earth?

  b to Jupiter, where gravity is stronger?

5 a Look at Table 3.1. Calculate the missing values i–v. Show your method.

Planet or asteroid	Object on planet or asteroid	Mass of object / kg	Acceleration due to gravity / m/s^2	Weight of object / N
Earth	astronaut	70	9.8	i
Moon	astronaut	ii	1.60	112.0
Jupiter	tin of beans	0.44	23.0	iii
Geographus (asteroid 1620)	bus	iv	0.00153	7.650
Toro (asteroid 1685)	astronaut	70	v	0.538

Table 3.1

  b What do you notice about the mass of the astronaut?

  c Explain why a tin of beans weighs more on Jupiter than a bus weighs on the asteroid Geographus.

3.3 Falling and turning

Objects fall to the ground because they have weight. Their weight is caused by the gravitational field of the Earth, pulling downwards on their mass. The Moon's gravitational field is much weaker, which is why objects weigh less when they are on the Moon.

In this section, we will look at two situations in which we have to take careful account of the directions of the forces acting on an object.

Falling through the air

The Earth's gravity is equally strong at all points close to the Earth's surface. If you climb to the top of a tall building, your weight will stay the same. We say that there is a uniform gravitational field close to the Earth's surface. This means that all objects fall with the same acceleration as the ball shown in Figure 3.10, provided there is no other force acting to reduce their acceleration. For many objects, the force of air resistance can affect their acceleration.

Parachutists make use of air resistance. A free-fall parachutist (Figure 3.12a) jumps out of an aircraft and accelerates downwards. Figure 3.12b shows the forces on a parachutist at different points in his fall. Notice that his weight does not change (so the length of the downward-pointing arrow does not change). At first, air resistance has little effect. However, air resistance increases with the speed of motion. As the parachutist falls faster, eventually air resistance balances his weight. Then the parachutist stops accelerating: he falls at a steady rate known as the **terminal velocity**. The resultant force on the free-fall parachutist is the result of two forces acting along the same line and acting in opposite directions.

terminal velocity: the greatest speed reached by an object when moving through a fluid

Opening the parachute greatly increases its area and hence the air resistance. Now there is a much bigger force upwards. The forces on the parachutist are again unbalanced, and he slows down. The idea is to reach a new, slower terminal velocity of about 10 m/s, at which speed he can safely land. At this point, weight = drag and so the forces on the parachutist are balanced.

Figure 3.12c shows how the parachutist's speed changes during a fall.

When the graph is horizontal, speed is constant and forces are balanced. When the graph is sloping, speed is

changing. The parachutist is accelerating or decelerating, and forces are unbalanced.

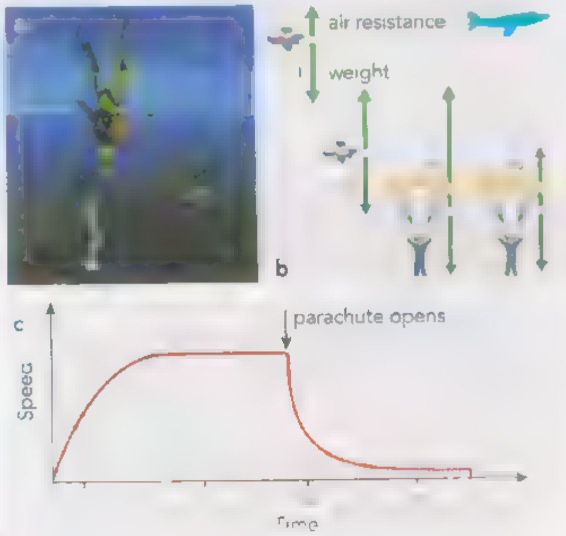


Figure 3.12a: Free-fall parachutists, before they open their parachutes. They can reach a terminal velocity of more than 50 m/s. **b:** The forces on a falling parachutist. Notice that his weight is constant. When air resistance equals weight, the forces are balanced and the parachutist reaches a steady speed. The parachutist is always falling (velocity downwards), although his acceleration is upwards when he opens his parachute. **c:** A speed–time graph for a falling parachutist.

Question

6 Look at the speed–time graph in Figure 3.12c. Find a point at which the graph is sloping upwards.
   - **a** Is the parachutist accelerating or decelerating?
   - **b** Which of the two forces acting on the parachutist is greater when the graph is sloping upwards?
   - **c** Explain the shape of the graph after the parachute is opened.

Going round in circles

When a car turns a corner, it changes direction. Any object moving along a circular path is changing direction as it goes. A force is needed to do this. Figure 3.13 shows three objects following curved paths, together with the forces that act to keep them on track.

In Figure 3.13a, the boy is spinning an apple around on the end of a piece of string. The tension in the string pulls on the apple, keeping it moving in a circle.

In Figure 3.13b, an aircraft 'banks' (tilts) to change direction. The lift force on its wings provides the necessary force.

In Figure 3.13c, the Moon is held in its orbit around the Earth by the pull of the Earth's gravity.

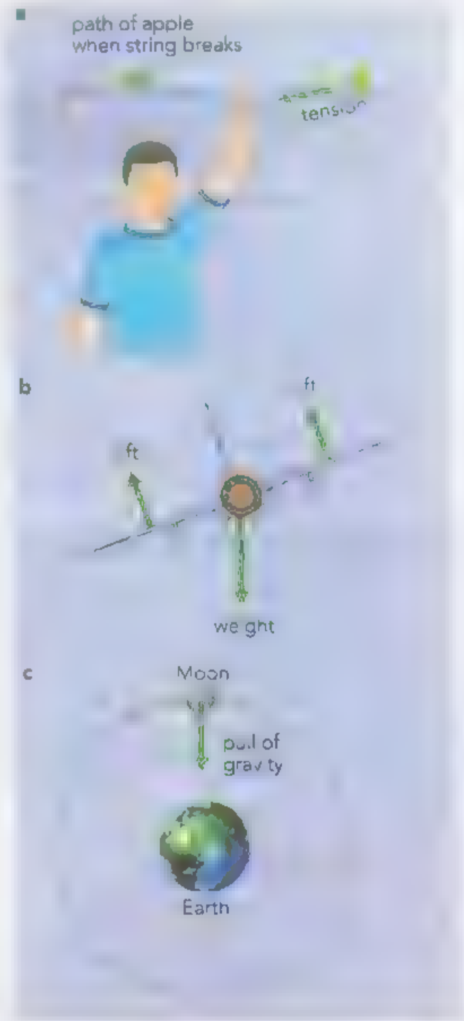


Figure 3.13: Examples of motion along a curved path. In each case, there is a sideways force holding the object in its circular path.

For an object following a circular path, the object is acted on by a force perpendicular (at right angles) to its motion. The force that keeps an object moving in a circle always acts towards the centre of the circle. If the force

disappears, the object will move off at a tangent to the circle, it will not fly outwards, away from the centre.

By moving in a circle, an object will be changing direction continuously (all the time). Therefore, even if the object is moving at a constant speed, its velocity is changing. Remember that velocity is a vector and so has direction as well as magnitude (size). If the velocity of an object is changing, it must be accelerating. This means that an unbalanced force is acting on the object and this force acts towards the centre of the circle. The resultant force that acts towards the centre of a circle is the result of a force acting perpendicular to the motion of the object.

The size of the resultant force needed to make an object travel in a circle depends on the object's mass, its speed and the radius of the circle in which it is moving. A bigger force is needed if:

- the object's mass is bigger (and speed and radius stay the same)
- the object's speed is bigger (and mass and radius stay the same)
- the radius of the circle is smaller (and mass and speed stay the same).

An object moving in a circle is changing direction. It requires less force to change the direction of an object that has less mass. An insect is easier to deflect than a rhinoceros, even if the rhino is moving slowly. When you are travelling in a car, you will feel a bigger force when you travel faster round a bend in the road or when the bend is sharper.

The 'wall of death' is a stunt where motorcycles or cars appear to defy gravity as they are driven around the circular wall inside a giant cylinder (Figure 3.14a). The vehicles do not slide down the wall because their weight is balanced by friction. As they move faster, the force of friction increases because the force pushing the vehicle towards the centre of the cylinder increases. If they were to stop, the vehicles would slide down the wall.

A spin dryer works by spinning about its axis of symmetry. The walls push the clothes towards the centre of the drum. Water droplets pass out through the holes where they do not experience this force.

Some of you will have ridden a carousel or merry-go-round (Figure 3.14b). Passengers sit on a circular platform that is made to spin. It feels like you are being pushed outwards, away from the centre, but this is an illusion. If you were lucky your merry-go-round had seats with a railing along the circumference where you could sit facing the centre; it would feel like the railing was pushing you towards the centre. Imagine the railings disappeared and there was nothing to hold onto. Where would you go? You would move at a tangent to the circular motion (along path A in Figure 3.1).

If you roll a ball along a flat surface it will move in a straight line until friction brings it to a stop. If someone pushes it at right angles to its motion, it will change direction. You may have seen a footballer gently tap a ball to divert it into the goal.

You might want to try the following challenge with a smaller ball. Gather some classmates around a square table. One of you rolls a marble or other small ball close to and parallel to an edge of the table. As the ball passes each person, they push it once with a flat edge like a ruler or book but only towards the centre of the table. See if you can get the ball to travel in a circle before it is slowed down by friction. As the ball slows down, you will notice that you need to apply a smaller force to keep it moving in a circle. If someone misses their turn, notice which way the ball moves. It should move in a straight

b

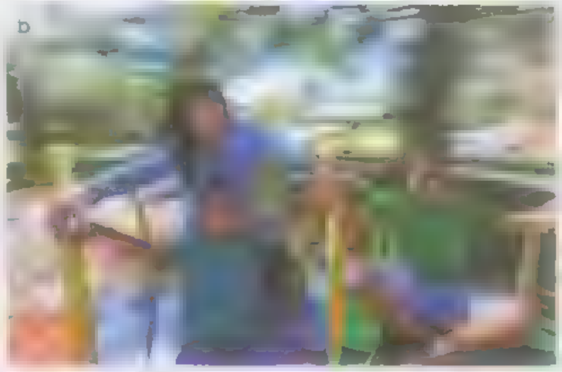


Figure 3.14a: The 'wall of death' in Rajkot, India
b: A mother and her sons playing on a merry-go-round

line at a tangent to the circle, so long as the table is perfectly horizontal and there is no spin on the ball. If the Sun suddenly stopped existing the Earth would travel in a straight line in the direction that it was moving the instant the Sun disappeared.

Questions

7 Draw a diagram (seen from above) to show the forces acting on a car as it turns a corner.

8 What provides the force keeping the planets in orbit round the Earth?

9 Throwing the hammer is an Olympic sport (Figure 3.15), where the thrower spins around inside a circle while swinging a 'hammer'. Throwers spin as fast as they can before releasing the hammer. Looking down from above, sketch the path of the hammer moving in a circle followed by its path after it is released.

Figure 3.15: Zheng Wang of China competes in the Women's hammer throw in the 2019 World Championships.

Describe how the force needed by the athlete would change if

- **a** the speed of the hammer increased
- **b** the length of the hammer was reduced
- **c** the mass of the hammer increased

3.4 Force, mass and acceleration

A car driver uses the accelerator pedal to control the car's acceleration. This alters the force provided by the engine. The bigger the force acting on the car, the bigger the acceleration it gives to the car. Doubling the force produces twice the acceleration, three times the force produces three times the acceleration, and so on.

There is another factor that affects the car's acceleration. Suppose the driver fills the boot with a lot of heavy boxes and then collects several children from college. He will notice the difference when he moves away from the traffic lights. The car will not accelerate so readily, because its mass has increased. Similarly, when he applies the brakes it will not decelerate as readily as before. The mass of the car affects how easily it can accelerate or decelerate. Drivers learn to take account of this.

The greater the mass of an object, the smaller the acceleration it is given by a particular force.

So, big (more massive) objects are harder to accelerate than small (less massive) ones. If we double the mass of the object, its acceleration for a given force will be halved. We need to double the force to give it the same acceleration.

This tells us what we mean by mass. It is the property of an object that resists changes in its motion.

Force calculations

These relationships between force, mass and acceleration can be combined into a single, very useful, equation.

force = mass × acceleration

$$F = ma$$

The force vector and the acceleration vector are in the same direction. This seems obvious when we are talking about increasing the engine force to make a car accelerate along a straight road, but recall from the previous section that the Earth must be accelerating towards the Sun because of the pull of the Sun's gravity.

The quantities involved in this equation, and their units, are summarised in Table 3.2. The unit of force is the newton. Worked Examples 3.1 and 3.2 show how to use the equation.

Quantity	Symbol	SI Unit
force	F	netwon, N
mass	m	kilogram, kg
acceleration	a	metres per second squared m/s²

Table 3.2: The three quantities related by the equation force = mass × acceleration

WORKED EXAMPLE [illegible]

When you strike a tennis ball that another player has hit towards you, you provide a large force to reverse its direction of travel and send it back towards your opponent. You give the ball a large acceleration What force is needed to give a ball of mass 0 10 kg an acceleration of 500 m/s²?

Step 1: Write down what you know and what you want to find out·

mass = 0.10 kg

acceleration = 500 m/s²

force = ?

Step 2: Substitute in the equation to find the force

force = mass × acceleration

$= 0.10\ \text{kg} \times 500\ \text{m/s}^2$

$= 50\ \text{N}$

Answer

You need to give the ball a force of 50 N.

Note that mass must be in kg (the base SI unit), not g, if the force is to work out in N.

WORKED EXAMPLE [illegible]

An Airbus A380 aircraft (Figure 3.16) has four jet engines, each capable of providing 320 000 N of thrust. The mass of the aircraft is 560 000 kg when loaded What is the greatest acceleration that the aircraft can achieve?

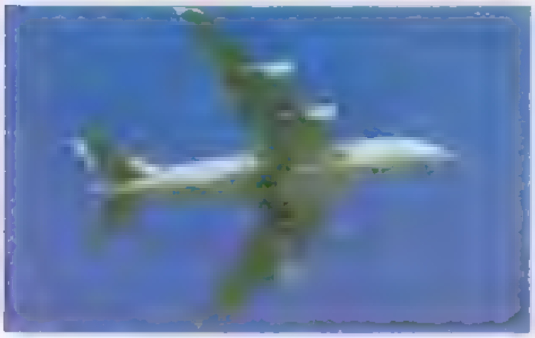


Figure 3.16:

Step 1: Write down what you know and what you want to find out

force = 4 × 320 000 N = 1 280 000 N (the greatest force provided by all four engines working together)

mass = 560 000 kg

acceleration = ?

Step 2: Substitute in the equation to find the acceleration

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}$$

$$= \frac{1280000\ \text{N}}{560000\ \text{kg}}$$

$$= 2.29\ \text{N/kg}$$

Answer

2.29 N/kg is the greatest acceleration the aircraft can achieve.

Questions

10 Look at Table 3.3. Calculate the missing values a–d. Show your working

Force	Mass	Acceleration / m/s²
a	50 kg	10
112 N	70 kg	b
110 kN	c	5
d	15 g	10

Table 3.3

11 a Calculate the weight of a brick that has a mass of 2.4 kg.

b The same brick falls with an acceleration of 9.8 m/s² Calculate the force on the brick

c What can you say about your answers to parts a and b?

12 An accelerometer is a device that can detect and calculate acceleration. Calculate the acceleration of a 0 15 kg mass that experiences a force of 10 N

ACTIVITY 3.[illegible]

Can mosquitoes fly in the rain?

Work in pairs. Using your physics knowledge and the information and data below, try to answer the question: can mosquitoes fly in the rain?

Once you have arrived at an answer, discuss it with another pair and be prepared to share your reasoning with the class.

If you are not sure where to start, work through the following questions:

1. What is the acceleration of the mosquito when hit by a raindrop in mid-air?
2. Calculate how many times bigger this is than the acceleration of free fall.
3. Do you think a human could survive this acceleration?
4. State the equation that relates force, mass and acceleration.
5. Calculate the force that the mosquito experiences.
6. Will a mosquito survive a mid-air collision with a raindrop?
7. Will a mosquito survive if it is sitting on a hard surface when struck with a raindrop? Calculate the force a raindrop would exert on a mosquito if the insect was sitting on a hard surface (such as a tree branch) and the raindrop came to a stop in 2×10^{-3} s.

In heavy rain, a mosquito might collide with a raindrop twice a minute.

If a raindrop hits a mosquito in mid-air, the mosquito falls with the raindrop for a few centimetres and the mosquito's speed increases from zero to 2.1 m/s in 1.5×10^{-3} s.

If a raindrop hits a mosquito when it is on a solid surface, such as a tree branch, the raindrop stops moving in 2×10^{-3} s.

speed of raindrops = 10 m/s

mass of raindrops = up to 100 mg

mass of mosquito = 2 mg

force that mosquito exoskeleton can survive = 0.03 N

Did you need to use the questions to help you during the activity? Using these questions gives you some insight into how scientists might go about answering a question: they break a question or problem down into smaller steps or questions.

Were the questions helpful? If not, can you think of questions that would be more helpful? Could you suggest other questions to your teacher or classmates?

3.5 Momentum

A force will change an object's motion. It will make the object accelerate; it may make it change direction. The effect of a force F depends on two things:

- how big the force is
- the time interval Δt it acts for.

The bigger the force and the longer it acts for, the more the object's motion will change. The impulse equation sums this up.

$F\Delta t = mv - mu$

The quantity on the left, $F\Delta t$, is called the **impulse** of the force. On the right we have mv (mass × final velocity) and mu (mass × initial velocity).

The quantity mass × velocity is known as the **momentum** (p) of the object ($p = mv$), so the right-hand side of the equation $mv - mu$ is the change in the object's momentum which can be written as:

$\Delta p = mv - mu = \Delta(mv)$

We can write the impulse equation like this:

impulse of force = change of momentum

Impulse and momentum are both defined by equations:

impulse = force × time for which it acts = $F\Delta t$

change in momentum = $\Delta p = \Delta(mv)$ so

impulse = $F\Delta t = \Delta(mv)$

impulse: the change in an object's momentum, Δp, or the force acting on an object multiplied by the time for which the force acts ($F \times \Delta t$)

momentum: the quantity mass × velocity, $p = mv$

momentum = mass × velocity

$$p = mv$$

impulse = force × time for which the force acts

impulse = $F\Delta t = \Delta(mv)$

A car of mass 600 kg is moving at 15 m/s.

a Calculate its momentum.

The driver accelerates gently so that a force of 30 N acts on the car for 10 seconds.

b Calculate the impulse of the force.

c Calculate the momentum of the car after the accelerating force has acted on it.

Answer

a momentum = mass × velocity

= 600 kg × 15 m/s = 9000 kg m/s

b impulse = force × time = 30 N × 10 s = 300 N s

c The impulse of the force tells us how much the car's momentum changes. The car is speeding up, so its momentum increases by 300 N s.

final momentum = initial momentum + impulse of force

= 9000 + 300

= 9300 kg m/s

Note that the unit of momentum is kg m/s; this is the same as N s, the unit of impulse.

Questions

13 Calculate the momentum of a bullet of mass 10.5 g moving at 553 m/s.

14 A force of 500 N acts on a rocket for 600 s, causing the rocket's velocity to increase.

- **a** Calculate the impulse of the force.
- **b** By how much does the rocket's momentum increase?

Remember that $F = ma$. We know that $a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$ so we can substitute for a to give:

$$F = m\left(\frac{v - u}{\Delta t}\right)$$

Expanding out the brackets gives:

$$F = \frac{mv - mu}{\Delta t}$$

Knowing that $\Delta p = mv - mu$, we can write the equation as:

$$F = \frac{\Delta p}{\Delta t}$$

$$\text{resultant force} = \frac{\text{change in momentum}}{\text{unit time}}$$

$$F = \frac{\Delta p}{\Delta t}$$

So, the resultant force is the change in momentum per unit time.

This defines the force as the rate of change of momentum but it is really just a different way of writing the more familiar equation $F = ma$ in a way that makes it easier to explain some physics. For example, it explains why cars are fitted with seatbelts, airbags and crumple zones. It also explains why we automatically bend our knees when we jump down from a tall object.

When a car crashes at a given speed say, (10 m/s), the passengers experience the same impulse or change in momentum whether or not they are wearing seatbelts. However, the time taken to come to a stop increases for those wearing seatbelts. This makes the right-hand side of the equation $\left(F = \frac{\Delta p}{\Delta t}\right)$ smaller. This reduces the force experienced by the passengers, which reduces the risk of injury. The same reasoning can be applied to other safety measures, including the use of air bags in Worked Example 3.4.

Crash tests allow scientists to investigate the forces on passengers during collisions. In the first test, a car travelling at 15 m/s crashes into a wall (Figure 3.17). The crash test dummy, which has a mass of 70 kg, comes to a stop in 0.03 s. In the second test, the car is fitted with an airbag so the dummy takes five times longer to come to a stop. What forces are acting on the dummy in both tests?

Figure 3.17: A crash test

Step 1: Start by writing down what you know and what you want to know.

First test	Second test
$m = 70\,\text{kg}$	$m = 70\,\text{kg}$
$v = 15\,\text{m/s}$	$v = 15\,\text{m/s}$
$\Delta t = 0.03\,\text{s}$	$\Delta t = 0.15\,\text{s}$
$F = ?$	$F = ?$

Step 2: Now write down the equation

$$F = \frac{\Delta p}{\Delta t}$$

Step 3: Substitute the values of the quantities on the right-hand side and calculate the answer.

First test	Second test
$F = \frac{70\,\text{kg} \times 15\,\text{m/s}}{0.03\,\text{s}}$	$F = \frac{70\,\text{kg} \times 15\,\text{m/s}}{0.15\,\text{s}}$
$= 3.5 \times 10^4\,\text{N}$	$= 7.0 \times 10^3\,\text{N}$

Answer

In the first test, the force on the crash test dummy was 3.5×10^4 N. In the second test, the force was 7.0×10^3 N. The airbag increased the time that it took for the dummy to come to a stop and reduced the force by a factor of five. An airbag reduces the risk of injury.

Question

15 In a car crash the driver and his passenger both experience the same impulse. However, the driver is wearing a seatbelt so it takes him longer to stop moving. Explain why his injuries are less serious than those of his passenger.

16 Superman is a fictional character who was made for life on the planet Krypton but arrived on Earth as a child. While he could have grown up to become average on Krypton, this question explores why he appears to have superpowers on Earth.

- **a** Write down an equation for force in terms of momentum and time.
- **b** Assume that Superman has a mass of 100 kg and launches himself upwards with a speed of 60 m/s. What force would he apply if he spent 0.25 s pushing off from the ground?
- **c** What is Superman's weight?
- **d** How many times bigger is the force (your answer to part **b**) compared to his weight (your answer to part **c**)?
- **e** Calculate the gravitational field strength of Krypton. (Hint: You need to know the value of the gravitational field strength for the Earth's surface and that, when most people jump, they apply a force approximately equal to their weight.)

Public awareness campaign

Work in pairs to develop your ideas and then join with another pair to complete the activity. Develop a public awareness campaign (posters, video clips) to highlight road traffic accidents (RTAs). The aim of your campaign is to reduce serious injury.

In your campaign make sure you include why the following are important in reducing serious injury in RTAs.

- keeping to speed limits
- wearing seatbelts
- installing airbags
- crumple zones on cars
- not driving after taking drugs
- not driving when tired.

Remember that the audience are not scientists, so you will need to explain, by using physics, why these precautions reduce serious injury in RTAs.

Momentum in a collision

Figure 3.18 shows a game of swing ball, in which a ball hangs from a length of string. The player hits the ball horizontally with a racket.

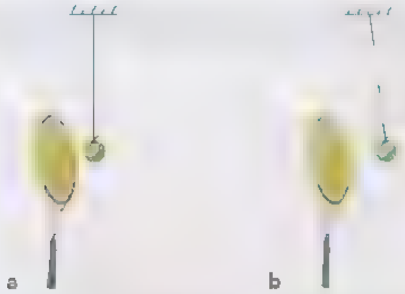


Figure 3.18: Hitting a ball with a tennis racket. **a:** Before the hit. **b:** after the hit.

How can we use the idea of momentum to describe what happens? We need to think about momentum before the racket collides with the ball, and then after the collision.

In Figure 3.18a, before the **collision**, the racket is moving to the right; it has momentum. The ball is stationary, so it has no momentum.

In Figure 3.18b, after the collision, the racket is moving to the right, but more slowly than before. It has lost momentum. The ball is moving rapidly to the right. It has gained momentum.

So you can see that, when the racket exerts a force on the ball, momentum is transferred from the racket to the ball. Whenever a force acts on an object, its momentum changes. At the same time, the momentum of the object causing the force also changes. If one object gains momentum, then the other loses an equal amount of momentum. This is known as the **principle of the conservation of momentum**.

collision: the meeting of particles or of bodies in which each exerts a force upon the other

principle of the conservation of momentum: the total momentum is constant and does not change because of an interaction between bodies (such as collisions)

We can state the principle in a different way. Whenever two objects interact, the total amount of momentum before they interact is the same as the total amount of momentum afterwards:

total momentum before = total momentum after

Worked Example 3.5 shows how we can use this to work out how fast the ball in Figure 3.18 will be moving after it has been hit by the racket.

During a game of swing ball, a player hits the ball horizontally with a racket.

- mass of tennis racket = 3.0 kg
- velocity of tennis racket before it strikes the ball = 20 m/s
- velocity of tennis racket after it strikes the ball = 18 m/s
- mass of tennis ball = 0.25 kg
- velocity of tennis ball before the racket strikes it = 0 m/s

Find:

a the momentum of the racket

i before the collision

ii after the collision

b the momentum of the ball after the collision

c the velocity of the ball.

Answer

a momentum = mass × velocity

i Before the collision

momentum = 3.0 kg × 20 m/s = 60 kg m/s

ii After the collision:

momentum = 3.0 kg × 18 m/s = 54 kg m/s

Note: After the collision, the racket is moving more slowly and so its momentum is less.

b The momentum gained by the ball is equal to the momentum lost by the racket.

So, momentum of ball = 60 kg m/s − 54 kg m/s

= 6.0 kg m/s

c We can calculate the velocity of the ball by rearranging the equation for momentum:

$$\text{velocity} = \frac{\text{momentum}}{\text{mass}} = \frac{6.0\ \text{kg m/s}}{0.25\ \text{kg}} = 24\ \text{m/s}$$

The ball will move off with a velocity of 24 m/s to the right.

[illegible]

Finding the velocity of a tennis ball using conservation of momentum

You want to carry out an investigation to find the speed of a tennis ball, but most of the instructions are missing. You need to finish the plan.

This is the only guidance you have.

> Equipment: tennis ball (or similar), cardboard box, newspaper or bubble wrap, stopwatch, measuring tape or metre rulers, mass balances
>
> Method: Fill a cardboard box with loosely crumpled newspaper or bubble wrap. Put the box on a smooth flat floor and throw the ball horizontally into the box (Figure 3.19). The box will slide before coming to a stop.

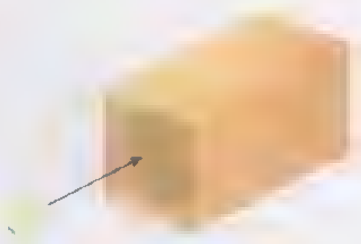


Figure 3.19

On your own, spend three minutes thinking carefully about the following activity and answer the questions. Then spend three minutes sharing ideas about the activity with the person sitting next to you. Be prepared to share your answers with the class.

Follow these steps to finish the plan.

1. Explain how the speed of the ball can be calculated using the principle of conservation of momentum (Hint: this is a collision between the ball and the box.)
2. Explain how the speed of the ball can be calculated using only the equipment available. It might help to sketch a speed-time graph for the box, as this will suggest what measurements you can take
3. Write down the steps (method) required to complete the investigation, including calculations needed and any safety precautions.

Optional

4. Compare your explanation and method with another group and improve your own.
5. If you have access to the equipment, carry out the experiment.
6. Using an alternative technique (such as video analysis) check whether you measured the correct speed and account for any difference.

[illegible]

Did the other group correctly and clearly:

- describe and explain what measurements to take?
- describe and explain what calculations to do?

Would you have been able to follow their method to produce reliable results?

Did the group include sensible safety precautions?

Provide constructive written and verbal feedback. As well as pointing out improvements, praise good aspects of their work.

When you get your work returned to you, make improvements based on the feedback.

3.6 More about scalars and vectors

You will recall that scalars have magnitude (size) only and no direction. We can represent forces using arrows because a force has a direction as well as a magnitude. This means that force is a vector quantity (see Chapter 2). Table 3.4 lists some scalar and vector quantities. Every vector quantity has a direction. However, it is not always necessary to state the direction if this is obvious for example, we might say, 'The weight of the block is 10 N,' without saying that this force acts downwards.

Scalar quantities	Vector quantities
distance	velocity
time	force
speed	weight
mass	acceleration
energy	momentum
temperature	electric field strength
	gravitational field strength

Table 3.4: Some scalar and vector quantities

Adding forces

What happens if an object is acted on by two or more forces? Figure 3.20a shows someone pushing a car. Friction opposes their pushing force. Because the forces are acting in a straight line, it is simple to calculate the resultant force, provided we take into account the directions of the forces:

resultant force = 500 N − 350 N

= 150 N to the right

Note that we must give the direction of the resultant force, as well as its magnitude. The car will accelerate towards the right.

Figure 3.20b shows a more difficult situation. A firework rocket is acted on by two forces.

- The thrust of its burning fuel pushes it towards the right.
- Its weight acts vertically downwards.

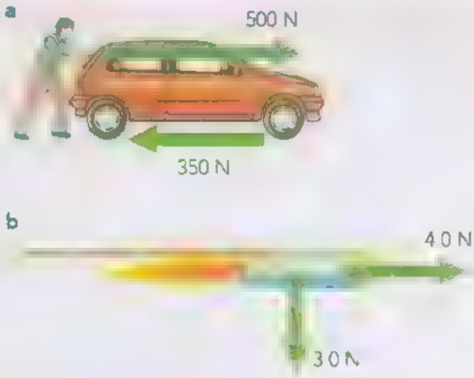


Figure 3.20a. Adding two forces in a straight line **b:** Adding two forces at right angles

Worked Example 3.6 shows how to find the resultant force by drawing a **vector triangle** (a graphical representation of vectors) or using Pythagoras' theorem.

> **vector triangle:** a graphical representation of vectors in two dimensions so that the resultant vector can be calculated

Rules for vector addition

You can add two or more forces using the following method. Simply keep adding arrows end-to-end.

- Draw arrows end-to-end, so that the end of one is the start of the next.
- Choose a scale that gives a large triangle.
- Join the start of the first arrow to the end of the last arrow to find the resultant.

Other vector quantities (for example, two velocities) can be added in this way. Imagine that you set out to swim across a fast-flowing river. You swim towards the opposite bank, but the river's velocity carries you downstream. Your resultant velocity will be at an angle to the bank.

Airline pilots must understand vector addition. Aircraft fly at high speed, but the air they are moving through is also moving fast. If they are to fly in a straight line towards their destination, the pilot must take account of the wind velocity (both its speed and direction).

Once you have mastered drawing a vector triangle, you could use Pythagoras' theorem to find the length of the resultant vector and trigonometry to find the angle.

WORKED EXAMPLE [illegible]

Find the resultant force acting on the rocket shown in Figure 3.20b. What effect will the resultant force have on the rocket?

Method 1: Draw a scale diagram

Step 1: Look at Figure 3.20b. The two forces are 4.0 N horizontally and 3.0 N vertically.

You now need to draw a scale diagram (a vector triangle) to represent these forces.

Use a scale of 1.0 cm to represent 1.0 N.

Step 2: Draw a horizontal arrow, 4.0 cm long, to represent the 4.0 N force. Mark it with an arrow to show its direction.

Step 3: Using the end of this arrow as the start of the next arrow, draw a vertical arrow, 3.0 cm long, to represent the 3.0 N force.

Step 4: Complete the triangle by drawing an arrow from the start of the first arrow to the end of the second arrow. This arrow represents the resultant force.

Step 5: Measure this arrow, and use the scale to determine the size of the force it represents.

length of line = 5.0 cm

resultant force = 5.0 N

Step 6: Use a protractor to measure the angle of the force. (You could also calculate this angle using trigonometry.)

angle of force = 37° below horizontal

Figure 3.21 shows what your vector triangle should look like.

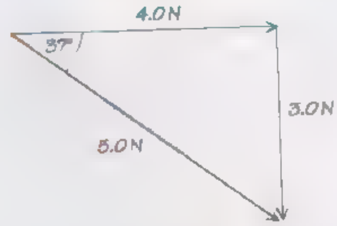


Figure 3.21: Vector triangle.

Method 2: Using Pythagoras' Theorem

Step 1: Look at Figure 3.20b. The two forces are at right angles so Pythagoras' theorem can be used. The square of the hypotenuse [illegible] opposite the right angle [illegible] of the squares of the other two sides.

Step 2: Find the resultant force using Pythagoras' theorem.

$c^2 = b^2 + a^2$

so $c = \sqrt{a^2 + b^2}$

so $c = \sqrt{4^2 + 3^2} = \sqrt{16 + 9} = \sqrt{25} = 5\text{ N}$

Step 3: Find the angle below the horizontal using trigonometry.

$\tan\theta = \dfrac{\text{opposite}}{\text{adjacent}} = \dfrac{3\text{ N}}{4\text{ N}}$

$\theta = \tan^{-1}\left(\dfrac{3}{4}\right) = 37°$

Answer

The resultant force acting [illegible] acting at 37° below the horizontal. [illegible] given an acceleration in this direction.

Notice that both methods give the same answer.

Question

17 You are rowing across the Lembeh Strait at 1.5 m/s.

a Calculate your velocity if you row against a current of [illegible] m/s?

b Use a vector triangle or calculate your resultant velocity [illegible] due south and [illegible] the east at 3 m/s. Give both your speed and direction.

Hyperloop One was described at the beginning of the chapter. If Hyperloop One is successful, trains will travel at high speed along tubes. It will use magnetic repulsion between two unlike magnetic poles to lift trains off the floor of the tubes to eliminate solid friction. By removing air from the tubes, the trains will push against less air resistance.

While we often want to reduce friction there are other situations where friction is helpful or even essential. Later you will discover other examples in physics where something can be both helpful and hazardous (for example, ionising radiation in Chapter 23).

Imagine that there is a character called Friction who has been charged with the crime of impeding the smooth running of the natural world. Evidence is collected for and against him before his case goes to trial.

Collecting evidence for the prosecution (against Friction)

Research at least one example that you have not already met in this chapter where it is helpful to reduce solid friction or drag.

Collecting evidence for the defence (of Friction)

Research at least one example of solid friction and one example of air resistance that is necessary or helpful. For example, we need solid friction between car tyres and the road. Without this friction a car would not be able to change speed (or start or stop) or change direction in order to follow the twists and turns in the road. However, this friction produces heat and this leads to wasted energy.

The judgement

Write the transcript from the trial (what was said and who said it). This might include statements by the prosecutor, defence lawyer, expert witnesses, and the trial judge.

Optional task: promoting an efficient mass transport system

By reducing friction, Hyperloop One promises more efficient use of energy. However, it requires the building of tubes for the trains to run inside, which requires building materials and energy for construction.

Use the Internet to find out about efficient mass transport systems (such as tram or subway systems for cities) that have a low carbon footprint. It could be an existing system or one that is proposed for the future (such as Hyperloop One). To learn about the maglev technology in Hyperloop One, you could read Chapter 16 to discover why magnets attract and repel.

Once you have found the most promising system, imagine that you are an environmental journalist with a physics background. Write an article (maximum 500 words) in support of it, which urges readers to pressure the government to adopt the transport system you are proposing. As well as writing something that grabs the attention of readers, you need to:

- justify why you support the system you have chosen, based on physics
- explain the relevant physics so that it can be understood by the public
- include relevant images.

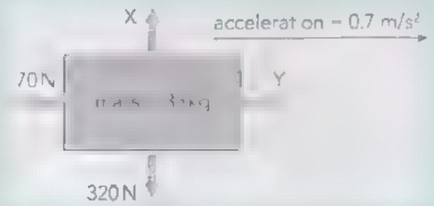
The unit of force is the newton (N)
Forces appear when two objects interact with each other.
A force can be represented by an arrow to show its direction, while length is proportional to the size of the force.
Solid friction, air resistance, and drag act in the opposite direction to the object's motion and can produce heating.
The resultant force is the single force that has the same effect as two or more forces.
A resultant force can change the speed and/or direction of an object.
The force of gravity pulls objects downwards and is normally called the weight of the object.
The acceleration caused by the pull of the Earth's gravity is called the acceleration of free fall or the acceleration due to gravity. It is given the symbol g and its value is 9.8 m/s² close to the surface of the Earth
The mass of an object, measured in kilograms, tells you how much matter that object is composed of.
The weight of an object, measured in newtons, is the gravitational force that acts on that object.
Terminal velocity is the name for the maximum constant speed reached when the resultant force acting on an object becomes zero It is often applied to parachutists when the upwards force of air resistance becomes equal and opposite to weight.
If an object moves in a circle, a force must be acting towards the centre of the path, perpendicular (at right angles) to the speed of the object.
For motion in a circular path, a bigger force is required if the body is more massive, moving faster or moving in a tighter circle.
Force = mass × acceleration, $F = ma$.
Momentum is the quantity mass × velocity, $p = mv$.
The principle of the conservation of momentum means that the total momentum after an interaction between bodies (for example, a collision) is the same as it was before the interaction.
The impulse (of a force) can be defined as the change in an object's momentum ($mv - mu$) or the force acting on an object multiplied by the time for which the force acts (Ft), so impulse = $F\Delta t$.
Force can be defined as the rate of change of momentum, $F = \frac{\Delta p}{\Delta t}$
The resultant of two vectors that do not act along the same line can be found by drawing a vector triangle or by calculation.

EXAM-STYLE QUESTIONS

1 In 2014, Alan Eustace set the world record for the highest freefall parachute jump (from a height of more than 41 km). As he fell towards the Earth, he reached a terminal velocity of almost 370 m/s. The air was very thin where he started his jump and became thicker the closer he got to the ground. What happened to his terminal velocity, before he opened his parachute? [1]

A it increased
B it stayed the same
C it reduced but not to zero
D it reduced to zero

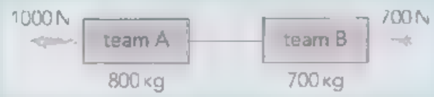
2 An object with a mass of 35 kg accelerates at 0.7 m/s² to the right, as shown in the diagram.



There are four forces acting on the object. What are the values of the forces labelled X and Y? [1]

A $X = 70$ N; $Y = 119.0$ N
B $X = 70$ N; $Y = 94.5$ N
C $X = 320$ N; $Y = 94.5$ N
D $X = 320$ N; $Y = 119.0$ N

3 This diagram shows the forces during a tug of war competition. Team A has a total mass of 800 kg and pulls with a force of 1000 N to the left. Team B has a total mass of 700 kg and pulls with a force of 700 N to the right. A strong rope joins them.



What is the acceleration of team A? [1]

A 0.20 m/s² to the left
B 1.25 m/s² to the right
C 1.25 m/s² to the left
D 0.38 m/s² to the left

4 These four diagrams show the forces on raindrops that are falling towards the ground.

Which raindrop is slowing down? [1]

NTINUE

[illegible]

to explain how seat belts and the crumple zones of a car help to reduce [illegible]

[Total: 7]

state: express in clear terms

calculate: work out from given facts, figures or information

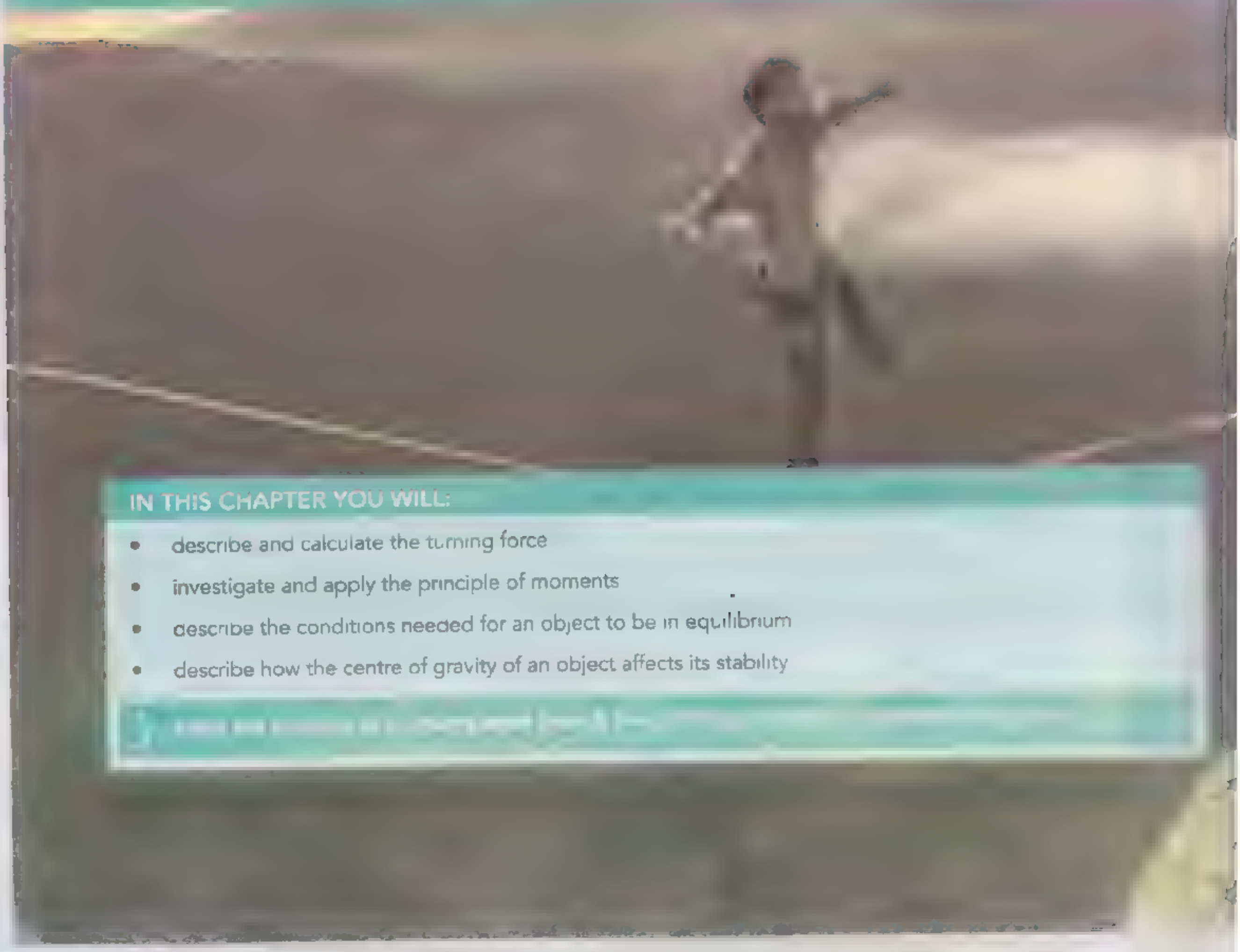
sketch: make a simple freehand drawing showing the key features, taking care over proportions

explain: set out purposes or reasons / make the relationships between things evident / provide why and / or how and support with relevant evidence

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	Needs more work	Almost there	Confident to move on
Recall the **two** ways that a force can change the motion of a body.	3.1			
Recall the significance of both the length and direction of arrows used to represent a force	3.1			
Recall that friction acts between two solid surfaces, friction acts in the opposite direction to motion and can produce thermal energy.	3.1			
Recall that air resistance and drag are like friction.	3.1			
Calculate the resultant force when two or more forces act along the same line.	3.1			
Define mass and weight and recall the differences between them, including the units used	3.2			
Recall that weight is the name given to the force of gravity on a body and that it always acts downwards.	3.2			
Recall and use the equation $W = mg$ and recall that $g = 9.8\ m/s^2$.	3.2			
Define terminal velocity.	3.3			
Recall the direction of the force that acts on a body to make it move in a circle.	3.3			
Recall how the size of the force that acts on a body to make it move in a circle depends on the mass and speed of the body and the radius of the circle.	3.3			
Recall and use the equations for force and momentum.	3.4, 3.5			
Define impulse and perform calculations by recalling and using the associated equations.	3.4			
Apply the principle of the conservation of momentum.	3.5			
Define what a force is and recall and use the associated equation.	3.4			
Calculate, or draw a vector triangle to work out, the resultant force when the forces do not act along the same line	3.6			



> Chapter 4

Turning effects

IN THIS CHAPTER YOU WILL:

- describe and calculate the turning force
- investigate and apply the principle of moments
- describe the conditions needed for an object to be in equilibrium
- describe how the centre of gravity of an object affects its stability

Spend 60 seconds thinking on your own, have 30 seconds of discussion with a partner and then be prepared to share your answers to the following questions with the class. You might find it helpful to draw sketches.

Explain how the street performer pictured in Figure 4.1a appears to levitate (float in space above the ground) and the performer shown in Figure 4.1b appears to defy the force of gravity.

Explain how lifeboats (see Figure 4.1c) can be self-righting (turn the right way up after capsizing).

Figure 4.1a: A street performer appears to levitate. **b:** A street performer appears to defy the force of gravity. **c:** An engraving of a self-righting lifeboat from the 19th century.

It is a sad fact that war creates opportunities for advances in technology. China invented the trebuchet in the 5th century and it was an effective siege weapon until the invention of gunpowder. A trebuchet is a catapult that has a swinging arm to fire a projectile (a thrown object).

The trebuchet is made from a long beam that pivots on an axle. The attacking soldiers attach a sling containing the projectile to the end of the longer section. They attach a counterweight to the shorter end. To fire the trebuchet, the soldiers allow the counterweight to fall which applies a turning force or moment on the beam. Because the projectile is further from the axle (or pivot), the projectile moves much faster than the counterweight and the sling at the end extends the effective length of the beam, making the projectile move even faster. The trebuchet uses energy transfers as well as turning forces. The largest trebuchets had a 15 metre beam, a 9000 kg counterweight and could hurl a 140 kg stone block to a range of almost 300 metres. Loup de Guerre (or Wolf of War) was the biggest trebuchet ever built, by Edward I, who was king of England in the late 13th century. He refused the surrender of Scottish defenders so that he could use it against Stirling Castle.

Discussion questions

1 Try explaining how a trebuchet works. Describe how the performance of the trebuchet would change if the projectile and counterweight swapped positions. Hint: Think about the relative speeds of the two ends of the beam. Draw a sketch if it helps.

2 A trebuchet uses energy transfers as well as turning forces. Can you think of other ideas in physics that need more than one topic to explain it?

3 What do you think would have done more damage to the walls of Stirling Castle: a projectile that is twice as massive or twice as fast? (If you have already met the equation for kinetic energy, see if you can work it out.)

Figure 4.2: Trebuchets are not a part of modern warfare. Here, an enthusiast uses his trebuchet to throw a pumpkin during a recent North American Pumpkin Launch.

4.1 The moment of a force

Figure 4.3 shows a boy who is trying to open a heavy door by pushing on it. He must make the **turning effect** of his force as big as possible. How should he push?

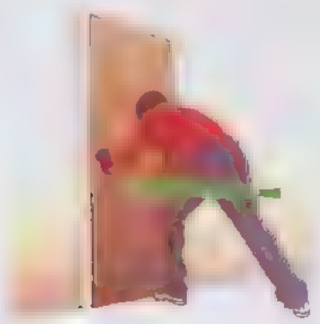


Figure 4.3: Opening a door – how can the boy have a big turning effect?

First of all, look for the **pivot** – the fixed point about which the door will turn. This is the hinge of the door. To open the door, the person must push with as big a force as possible, and as far as possible from the pivot – at the other edge of the door. (That is why the door handle is fitted there.) To have a big turning effect, the person must push hard at right angles to the door. Pushing at a different angle gives a smaller turning effect.

The quantity that tells us the turning effect of a force about a pivot is its **moment**.

- The moment of a force is bigger if the force is bigger.
- The moment of a force is bigger if it acts further from the pivot.
- The moment of a force is greatest if it acts at 90° to the object it acts on.

KEY WORDS

turning effect: when a force causes an object to rotate or would make the object rotate if there were no resistive forces

pivot: the fixed point about which a lever turns; also known as the fulcrum

moment: the turning effect of a force about a pivot, given by force × perpendicular distance from the pivot

Making use of turning effects

Figure 4.4 shows how understanding moments can be useful.

When using a crowbar to lift a heavy rock, pull near the end of the bar, and at 90°, to have the biggest possible turning effect.

When lifting a load in a wheelbarrow, the long handles help to increase the moment of the lifting force.

Figure 4.4: Understanding moments can help in some difficult tasks

Balancing a beam

Figure 4.5 shows a small child sitting on the left-hand end of a see-saw. Her weight causes the see-saw to tip down on the left. Her father presses down on the other end. If he can press with a force greater than her weight, the see-saw will tip to the right and she will come up in the air.

Now, suppose the father presses down closer to the pivot. He will have to press with a greater force if the turning effect of his force is to overcome the turning effect of his daughter's weight. If he presses at half the distance from the pivot, he will need to press with twice the force to balance her weight.

Figure 4.5: Two forces are causing this see-saw to tip. The girl's weight causes it to tip to the left, while her father provides a force to tip it to the right. He can increase the turning effect of his force by increasing the force, or by pushing down at a greater distance from the pivot.

A see-saw is an example of a beam, a long, rigid object that is pivoted at a point. The girl's weight is making the beam tip one way. The father's push is making it tip the other way. If the beam is to be balanced, the moments of the two forces must cancel each other out.

Equilibrium

In science and in other subjects, you will often hear about things that are in equilibrium. This always means that two or more things are balanced. When a beam is balanced, we say that it is in equilibrium. When an object is in equilibrium:

- the forces on it must be balanced (no resultant force)
- the turning effects of the forces on it must also be balanced (no resultant turning effect).

When a resultant force acts on an object, it will start to move off in the direction of the resultant force. If there is a resultant turning effect, it will start to rotate.

equilibrium: when no net force and no net moment act on a body

Questions

1 Choose the correct option in the following statements.
   a The moment of a force is bigger if the force is {smaller / bigger}.
   b The moment of a force is bigger if it acts {closer / further} from the pivot.
   c The moment of a force is greatest if it acts at {0° / 45° / 90°} to the object it acts on.

2 Three different forces are pulling on a heavy trapdoor (Figure 4.6). Which force will have the biggest turning effect? Explain your answer.

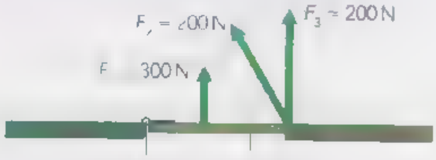


Figure 4.6

3 Explain why somebody would use a spanner with a longer handle if they needed to undo a tight bolt.

4 a Explain why a tree is more likely to be blown over in a stronger wind.
   b Explain why a taller tree is more likely to be blown over than a shorter tree.

4.2 Calculating moments

We have seen that, the greater a force and the further it acts from the pivot, the greater is its moment. We can write an equation for calculating the moment of a force like this:

moment of a force = force × perpendicular distance from the pivot

Now let us consider the unit of moment. Since moment is a force (N) multiplied by a distance (m), its unit is simply the newton metre (Nm). There is no special name for this unit in the SI system. Take care: if distances are given in cm, the unit of moment will be Ncm. Take care not to mix these different units (Nm and Ncm) in a single calculation.

Figure 4.7 shows an example. The 40 N force is 2.0 metres from the pivot, so:

moment of force = 40 N × 2.0 m = 80 Nm

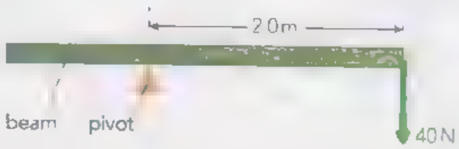


Figure 4.7: Calculating the moment of a force

Balancing moments

Look back at Figure 4.5, where a father and his daughter are playing on a see-saw. On her own, she would make the see-saw turn **anticlockwise**; her weight has an anticlockwise moment. To make the see-saw balance, her father needs to push down on the right-hand end of the see-saw, applying a **clockwise** moment.

The idea that an object is balanced when clockwise and anticlockwise moments are equal is known as the **principle of moments**. We can use this principle to find the value of an unknown force or distance, as shown in Worked Example 4.1.

[illegible]

The daughter in Figure 4.5 has a weight of 500 N and is sitting 2.0 metres to the left of the pivot. Her father has a weight of 800 N. How far to the right of the pivot should he sit so that the see-saw is balanced?

Step 1: Write down what you know and what you want to find out.

anti-clockwise force = 500 N
distance = 2.0 m
clockwise force = 800 N; distance = ?

Step 2: Since the see-saw has to be in equilibrium, we can write:

total anticlockwise moment = total clockwise moment

Step 3: Substitute in the values from Step 1, and solve.

$500\ \text{N} \times 2.0\ \text{m} = 800\ \text{N} \times \text{perpendicular distance}$

$1000\ \text{Nm} = 800\ \text{N} \times \text{perpendicular distance}$

$$\text{perpendicular distance} = \frac{1000\ \text{Nm}}{800\ \text{N}} = 1.25\ \text{m}$$

Answer

The father needs to sit 1.25 m to the right of the pivot so that the see-saw is balanced.

Questions

5 Write down, in words, the equation for finding the moment of a force about a point, stating carefully the units for each quantity.

6 A bolt is tightened by applying a turning force of 30 N to the end of the spanner (Figure 4.8).

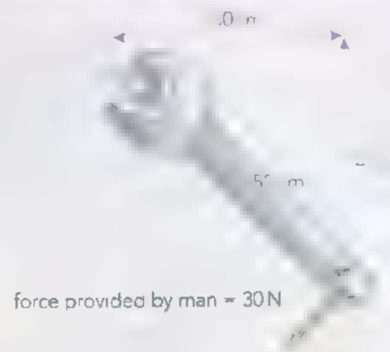


Figure 4.8

a Which of the three distance measurements should you use?

b Use this distance to calculate the moment.

7 A uniform metre ruler is balanced at its midpoint (Figure 4.9).

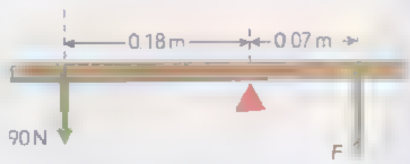


Figure 4.9

Calculate the unknown force F.

8 A boy of mass 60 kg, and his sister of mass 49 kg, play on a see-saw pivoted at its centre. If the boy sits 2.7 metres from the pivot of the see-saw, calculate the distance from the other side of the pivot the girl must sit to make the see-saw balanced.

[illegible]

anticlockwise: turning in the opposite direction from the hands on a clock

clockwise: turning in the same direction as the hands on a clock

principle of moments: when an object is in equilibrium, the sum of anticlockwise moments about any point equals the sum of clockwise moments about the same point

Moving fingers along a metre ruler

Work with a partner. Take it in turns to balance a metre ruler (or a pair of round pencils) across your index fingers with your hands wide apart but at different distances from the ends of the ruler. Slowly bring your hands together. Discuss what you observe with your partner. As part of your discussions, you both need to describe and explain what you observe.

Now work independently to write a description and an explanation. Your description should include a diagram of what was happening. You can label the diagram as part of your explanation, which needs to include the following words: moments, centre of gravity, and friction.

When you have both finished writing, swap your work and decide who has written the better explanation and why it is better. For example, is it clearer or more scientifically accurate? Update your own work with any improvements.

Now try the same thing with a 100 g mass taped somewhere to the ruler (or use a pool cue if available). What do you observe this time? Can you explain what is happening?

You need to describe and explain as you did before.

More balancing moments

The three children in Figure 4.10 have balanced their see-saw – it is in equilibrium. The weight of the child on the left is tending to turn the see-saw anticlockwise. So the weight of the child on the left has an anticlockwise moment. The weights of the two children on the right have clockwise moments. From the data in Figure 4.10 we can calculate these moments:

anticlockwise moment = 500 N × 2.0 m = 1000 Nm

clockwise moments = (300 N × 2.0 m) + (400 N × 1.0 m)

= 600 Nm + 400 Nm

= 1000 Nm

The brackets are included as a reminder to perform the multiplications before the addition.

We can see that, in this situation:

total clockwise moment = total anticlockwise moment

So the see-saw in Figure 4.10 is balanced.

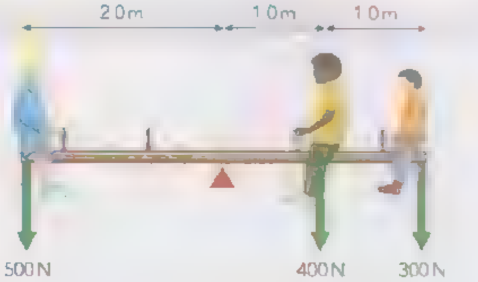


Figure 4.10: A balanced see-saw. On her own, the child on the left would make the see-saw turn anticlockwise; her weight has an anticlockwise moment. The weight of each child on the right has a clockwise moment. Since the see-saw is balanced, the sum of the clockwise moments must equal the anticlockwise moment.

The beam shown in Figure 4.11 is 2.0 metres long and has a weight of 20 N. It is pivoted as shown. A force of 10 N acts downwards at one end. What force F must be applied downwards at the other end to balance the beam?

Figure 4.11: Balancing a beam

Step 1: Identify the clockwise and anticlockwise forces. Two forces act clockwise: 20 N at a distance of 0.5 m, and 10 N at 1.5 m. One force acts anticlockwise: the force F at 0.5 m.

Step 2: Since the beam is in equilibrium, we can write: total clockwise moment = total anticlockwise moment

Step 3: Substitute in the values from Step 1, and solve.

$$(20\text{ N} \times 0.5\text{ m}) + (10\text{ N} \times 1.5\text{ m}) = F \times 0.5\text{ m}$$
$$10\text{ Nm} + 15\text{ Nm} = F \times 0.5\text{ m}$$
$$25\text{ Nm} = F \times 0.5\text{ m}$$
$$F = \frac{25\text{ Nm}}{0.5\text{ m}}$$
$$= 50\text{ N}$$

Answer

A force of 50 N must be applied downwards at the other end to balance the beam.

You might have been able to work this out in your head, by looking at the diagram. The 20 N weight requires 20 N to balance it, and the 10 N at 1.5 m needs 30 N at 0.5 m to balance it. So the total force needed is 50 N.

In equilibrium

In Figure 4.10, three forces are shown acting downwards. There is also the weight of the see-saw itself, 200 N, to consider, which also acts downwards, through its midpoint. If these were the only forces acting, they would make the see-saw accelerate downwards. Another force acts to prevent this from happening. There is an upward contact force where the see-saw sits on the pivot. Figure 4.12 shows all five forces.

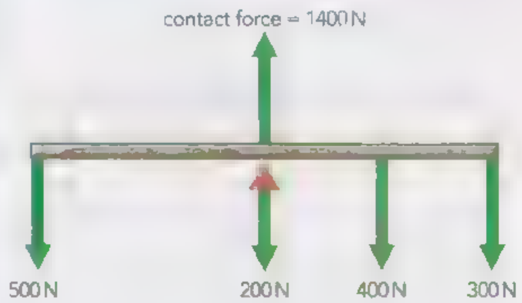


Figure 4.12: A force diagram for the see-saw shown in Figure 4.10. The upward contact force of the pivot on the see-saw balances the downward forces of the children's weights and the weight of the see-saw itself. The contact force has no moment about the pivot because it acts through the pivot. The weight of the see-saw is another force that acts through the pivot, so it also has no moment about the pivot.

Because the see-saw is in equilibrium, we can calculate this contact force. It must balance the four downward forces, so its value is (500 + 200 + 400 + 300) N = 1400 N, upwards. This force has no turning effect because it acts through the pivot. Its distance from the pivot is zero, so its moment is zero.

Now we have satisfied the two conditions that must be met if an object is to be in equilibrium:

- there must be no resultant force acting on it
- total clockwise moment = total anticlockwise moment

You can use these two rules to solve problems concerning the forces acting on objects in equilibrium.

Sometimes we know that the forces and moments acting on an object are balanced. Then we can say that it is in equilibrium. Sometimes we know the reverse, namely, that an object is in equilibrium. Then we can say that there is no resultant force on it, and no resultant moment.

Questions

9 A uniform metre ruler is balanced at its centre (Figure 4.13).

Figure 4.13: Balanced uniform metre ruler

  a Calculate the distance to the right of the pivot that the 125 N load needs to be placed for the ruler to be balanced.

  b Calculate the contact force acting at the pivot.

10 A beam is balanced on a pivot 0.33 metres from its left hand side (Figure 4.14).

The beam balances when a weight of 0.47 N is suspended 0.13 metres from the same end.

Figure 4.14: Balanced beam.

  a Calculate the anticlockwise moment of the 0.47 N force.

  b What is the moment due to the weight of the rod?

  c The weight of the rod is 0.79 N. Calculate the position of its centre of gravity to the right of the pivot.

EXPERIMENTAL SKILLS 4.1

A question of balance

Engineers need to design structures that do not fall down when the forces on them change location or magnitude (size). For example, a building needs to stay standing when wind blows against it with different strengths or from different directions. Bridges should not bend or collapse when vehicles cross them. You will test whether there is a resultant moment on an object that is in equilibrium. You will test the moment of a force and the principle of moments in this experiment.

You will need

- a metre ruler
- two 10 N spring balances
- set of 100 g masses
- two clamp-stands with clamps and bosses
- three cotton loops

Safety: Take care not to drop the masses on your feet.

Getting started

- What is meant by equilibrium?
- What is the moment of a force?
- What is the principle of moments?
- Where would you expect the centre of gravity to be for a metre ruler?
- Figure 4.15 shows a lorry about to be driven across a bridge supported by columns A and B. Describe the force at column A as the lorry travels between A and B and then beyond column B.

Figure 4.15: Lorry on a bridge

Method

1 Set up the apparatus as shown in Figure 4.16 with the loops for the spring balances about 5 cm from each end of the ruler. You are going to move the load to different positions along the ruler. Make sure that the ruler is horizontal before you take each measurement by moving the clamps holding one of the spring balances up or down its clamp-stand.

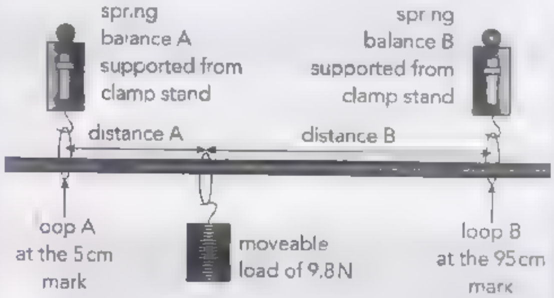


Figure 4.16: Apparatus for investigation.

2 Hang the 9.8 N from the ruler so that distance A = 10 cm and distance B = 80 cm.

3 Note down the readings on both of the spring balances, F_A and F_B, and calculate $(F_A + F_B)$. Record all the values in a copy of the table below:

Distance from A / m	F_A / N	F_B / N	$F_A + F_B$ / N
0.1			

4 Move the load about 10 cm along the ruler towards B. Make sure the ruler is horizontal and then record all the measurements required to complete the next row of the table.

5 Repeat this process until the load is at a distance of 0.8 m from A.

6 On the same axes, plot line graphs of F_A, F_B and $F_A + F_B$ on the vertical axis against the distance from A on the horizontal axis.

Questions

1 Why did you have to make sure that the ruler was horizontal before each measurement was made?

2 Calculate the mean of your ($F_A + F_B$) values. This should be more than the load of 9.81 N hanging from the ruler. Can you explain why?

3 Measure the mass of the ruler and work out its weight. Does this account for the difference in the last question?

4 Instead of doing the experiment, it can be solved mathematically by taking moments about either spring balance. For example, the force at spring balance A, F_A, can be solved by taking moments about B (and taking into account of the ruler to get a more accurate result).

Understanding the shadoof

The Ancient Egyptians used the shadoof to lift water and irrigate the land. It is still in use today (see Figure 4.17).

Figure 4.17: A Sudanese man irrigates his land using a shadoof.

The shadoof has a counterweight at the short end and a bucket at the long end of a beam. It takes as much effort to move the bucket down as it does to pull it up.

Unless your teacher gives you a time, spend one minute thinking on your own, one minute of discussion with your neighbour and then be prepared to share your answers to question 1 with the class.

1 a What is the advantage of making it take as much effort to push the bucket down as it does to pull it up?

b Explain how the shadoof does this.

2 Draw a diagram of the shadoof and include the pivot, the counterweight and the forces acting on it. You could estimate the lengths of the beam and assume that the counterweight has a weight of 150 N.

If you are given time and the equipment, make a working model.

Did you understand the physics in Activities 4.1 and 4.2? A good test of your understanding is whether you can explain it clearly. Are you able to support your explanations with clear and correct force diagrams? If you are still unsure, ask a classmate to explain it.

4.3 Stability and centre of gravity

People are tall and thin, like a pencil standing on end. Unlike a pencil, we do not topple over when touched by the slightest push. We are able to remain upright, and to walk, because we make continual adjustments to the positions of our limbs and body. We need considerable brain power to control our muscles for this. The advantage is that, with our eyes about a metre higher than if we were on all-fours, we can see much more of the world.

Circus artistes such as tightrope walkers and high-wire artistes (Figure 4.18) have developed the skill of remaining upright to a high degree. They use items such as poles or parasols to help them maintain their balance. The idea of moments can help us to understand why some objects are stable while others are more likely to topple over.

Figure 4.18: This high-wire artiste is using a long pole to maintain her stability on the wire. If she senses that her weight is slightly too far to the left, she can redress the balance by moving the pole to the right. Frequent, small adjustments allow her to walk smoothly along the wire.

A tall glass can be knocked over easily – it is unstable. Figure 4.19 shows what happens if the glass is tilted.

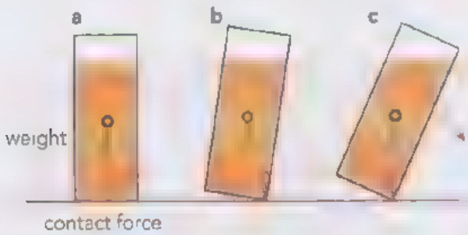


Figure 4.19: A tall glass is easily toppled. Once the line of action of its weight is beyond the edge of the base the glass tips right over.

In Figure 4.19a, the glass is upright. Its weight acts downwards and the contact force of the table acts upwards. The two forces are in line, and the glass is in equilibrium.

In Figure 4.19b, the glass is tilted slightly to the right, and the forces are no longer in line. There is a pivot at the point where the base of the glass is in contact with the table. The line of the glass's weight is to the left of this pivot, so it has an anticlockwise moment, which tends to tip the glass back to its upright position.

In Figure 4.19c, the glass is tipped further. Its weight acts to the right of the pivot, and has a clockwise moment, which makes the glass tip right over.

Centre of gravity

In Figure 4.19, the weight of the glass is represented by an arrow starting at a point inside the liquid. Why is this? The reason is that the glass behaves as if all of its mass were concentrated at this point, known as the centre of gravity. The force of gravity acts on the mass of the glass – each bit of the glass is pulled by the Earth's gravity. However, rather than drawing lots of weight arrows, one for each bit of the glass, it is simpler to draw a single arrow acting through the centre of gravity. (Because we can think of the weight of the glass acting at this point, it is sometimes known as the centre of gravity.)

stable: an object that is unlikely to topple over, often because it has a low centre of gravity and a wide base

unstable: an object that is likely to topple over, often because it has a high centre of gravity and a narrow base

centre of gravity: all the mass of an object could be located here and the object would behave the same (when ignoring any spin)

Figure 4.20 shows the position of the centre of gravity for several objects. A person is fairly symmetrical, so their centre of gravity must lie somewhere on the axis of symmetry. (This is because half of their mass is on one side of the axis, and half on the other.) The centre of gravity is in the middle of the body, roughly level with the navel. A ball is much more symmetrical, and its centre of gravity is at its centre.

For an object to be stable, it should have a low centre of gravity and a wide base. The pyramid in Figure 4.20 is an example of this. The high-wire artiste shown in Figure 4.18 has to adjust her position so that her centre of gravity remains above her base, which is the point where her feet make contact with the wire.

Figure 4.20: The weight of an object acts through its centre of gravity. Symmetry can help to judge where the centre of gravity lies. An object's weight can be considered to act through this point. Note that, for the table, its centre of gravity is in the air below the table top

Finding the centre of gravity

Balancing is the clue to finding an object's centre of gravity. A metre ruler balances at its midpoint, so that is where its centre of gravity must lie.

The procedure for finding the centre of gravity of a more irregularly shaped object is shown in Figure 4.21. In this case, the object is a piece of card, described as a plane lamina. The card is suspended from a pin. If it is free to move, it hangs with its centre of gravity below the point of suspension. This is because its weight pulls it round until the weight and the contact force at the pin are lined up. Then there is no moment about the pin. A plumb-line is used to mark a vertical line below the pin. The centre of gravity must lie on this line.

The process is repeated for two more pinholes. Now there are three lines on the card, and the centre of gravity must lie on all of them, that is, at the point where they intersect. Two lines might have been enough, but it is advisable to use at least three points to reveal any inaccuracies.

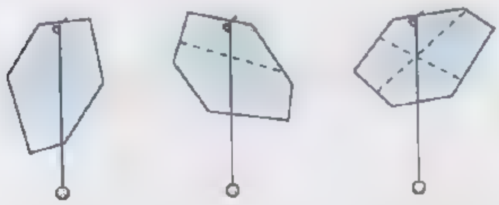


Figure 4.21: Finding the centre of gravity of an irregularly shaped piece of card. The card hangs freely from the pin. The centre of gravity must lie on the line indicated by the plumb-line hanging from the pin. Three lines are enough to find the centre of gravity

lamina flat two-dimensional shape

EXPERIMENTAL SKILLS 4.2

Centre of gravity of a plane lamina

You will investigate a technique for finding the centre of gravity of a piece of rectangular card. Once you gain confidence that the technique works, you will apply it to an irregular shape, perhaps the map of your country. Locating the centre of gravity of a body is important when considering its stability

You will need:

- at least two pieces of card
- a hole punch
- a pencil
- a pair of scissors
- a ruler
- a clamp stand and boss
- a pin (or short thin metal rod)
- a length of string with a weight (plumb bob) attached

Safety: The pin and the scissors should be [illegible]

Getting started

- Predict where the centre of gravity is located on the rectangular lamina.
- Predict where the centre of gravity is located on the shape you propose.
- Can you suggest shapes where the centre of gravity would not be on the card?

Method: Part 1

Find the centre of gravity of a rectangular sheet of card. This is your lamina.

1 Use the hole punch to make three holes far apart around the edge of the lamina
2 Fix the pin horizontally in the clamp.
3 Using one hole, hang the lamina from the pin Make sure that it can swing freely
4 Hang the string from the pin so that the weight makes it hang vertically. Mark two points on the lamina along the length of the string.
5 Repeat steps 3 and 4 using the other two holes.
6 Lay the lamina on the bench and, using a ruler, draw lines joining each pair of points. Where the lines cross is the centre of gravity of the lamina. It should be where the lines of symmetry coincide but, if the three lines cross exactly at a point, you have done well!

Method: Part 2

Repeat part 1 after you have cut a shape out of the lamina. See if you can get a map of your country printed on the card so that you can find its centre of gravity

Questions

1 Did the three lines you drew intersect at the same point?
2 If the three lines did not intersect at the same point, how did you decide where the centre of gravity is located?
3 If the three lines did not intersect at the same point, how much confidence do you have in the location you have chosen?
4 Suggest a way of checking that you have located (found) the centre of gravity?
5 Explain why the centre of gravity of the lamina lies on a vertical line below the pin (pivot).

…SMENT

Swap your work with a partner for Experimental skills 4.2.

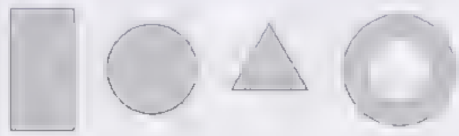
Give them a smiley face for the following:

- three neatly drawn and closely intersecting lines on their rectangular lamina (as this shows careful experimental technique)
- three closely intersecting lines on their irregular shape
- correct answer to the Getting Started questions
- a clear and correct explanation of why the centre of gravity is vertically below the pivot

Finally, discuss anything that you can learn from each other.

Questions

11 On a copy of the shapes below, mark the centre of gravity for each with an X. Where possible, show lines that helped you locate the centre of gravity.



a b c d

Figure 4.22: Laminar shapes

12 Buses and other vehicles have to be tilt tested to an angle of at least 28 degrees from the vertical before they can carry passengers.

Figure 4.23: Both of these double decker buses would topple over if tilted any further.

a Use the ideas of stability and centre of gravity to explain why either bus in Figure 4.23 would topple over if tilted any further. You can draw on copies of the diagrams to help with your explanation.

b Explain how the stability of the bus would be affected by having more passengers on the upper deck.

c Explain why bags of sand are only put on the top deck of bus B and not the lower deck.

13 Figure 4.24 shows the forces acting on a cyclist.

a Explain how you can tell that the cyclist shown in Figure 4.24a is in equilibrium.

b Are the forces on the cyclist in Figure 4.24b balanced now? How can you tell?

c Would you describe the cyclist as stable or unstable? Explain your answer.

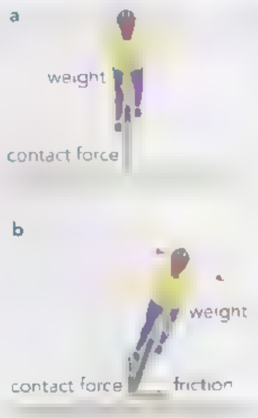


Figure 4.24: Forces acting on a cyclist

PROJECT

The Italian Job

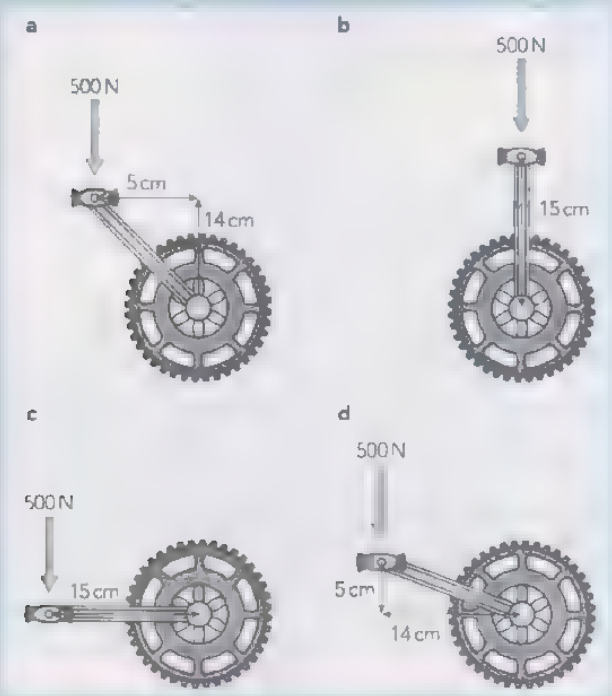
The Italian Job was a film made in 1969. In this film a gang steals gold worth $4 million in Turin, northern Italy. As the gang escapes through Switzerland on a bus, the driver loses control. The bus ends up with its rear half hanging over the edge of a vertical drop. Any attempt to reach the gold at the back of the coach risks sending the bus, the men and the gold crashing into the valley below. The film finishes with Croker saying: 'Hang on a minute lads, I've got a great idea'. The film is available online but only the last five minutes are important from a physics viewpoint.

- You need to suggest what Croker's 'great idea' might have been to save the gold and get off the coach safely. You should work in groups of three.
- Start by describing the problem using correct scientific terms like 'pivot', 'centre of gravity', 'equilibrium', 'moment' and 'the principle of moments'.
- Make a storyboard of your solution and include it as part of a two-minute pitch for a sequel to the film.
- Select the best pitch (with correct or corrected physics) from three or four groups of three to present to the rest of the class.

The moment of a force is a measure of its turning effect.
Increasing force or distance from the pivot increases the moment of a force.
Moment of a force = force × perpendicular distance from the pivot.
An object is in equilibrium when the forces on it are balanced (no resultant force) and the turning effects of the forces on it are balanced (no resultant turning effect).
The centre of gravity is the point at which the weight of an object appears to be concentrated
The location of the centre of gravity affects stability

EXAM STYLE QUESTIONS

1 **The pictures show different positions of a bicycle pedal. Which position would result in the biggest turning force?** **[1]**



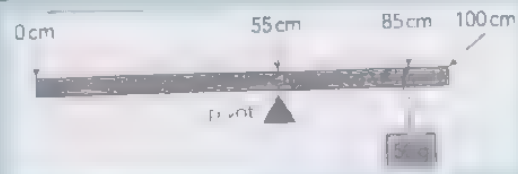
2 This is a plan view of a gate that will swing open about the pivot shown. Also shown are the positions for a motor and the direction they will move the gate. The length of the arrows indicates the size of the force. Choose the arrow that will swing the gate open the quickest. [1]

3 A toy train is crossing a bridge.

The centre of gravity of the train is mid-way between the supports. Which row of the table shows the correct values of the contact forces at X and Y? [1]

	Force X/N	Force Y/N
a	8	0
b	0	8
c	4	4
d	8	8

4 A 1.0 metre wooden ruler is damaged and no longer uniform. The mass of the ruler is 11.5 g. The ruler is balanced on a pivot with a 50 g mass as shown.



Where is the centre of gravity of the ruler? [1]

A at the 13 cm mark

B at the 42 cm mark

C at the 60 cm mark

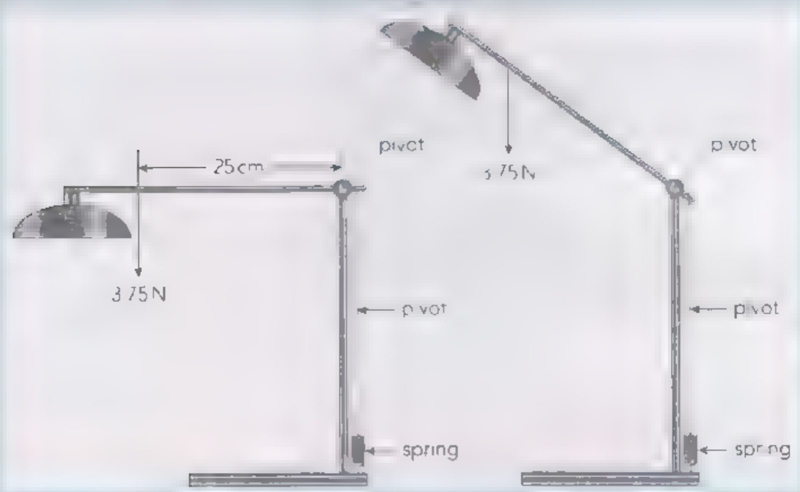
D at the 68 cm mark

5 State two ways that the turning force can be increased. [2]

6 State two pieces of evidence that would tell you that a body is not in equilibrium. [2]

7 The diagram shows an angle-poise lamp. The light is at the end of an arm. The arm can be moved about the pivot. The cord passes vertically down to a stretched spring.

The weight of the lamp and arm is 3.75 N and acts at a distance of 25 cm from the pivot.



a Write down the equation used to calculate the moment of a force. [1]

b Calculate the moment of the 3.75 N force about the pivot when the arm is horizontal. [2]

c The arm is raised as shown in the diagram.

i Explain what has happened to the moment of the 3.75 N force about the pivot. [1]

ii Explain what has happened to the clockwise moment produced by the spring. [1]

[Total: 5]

state: command term not supplied

calculate: work out from given facts, figures or information

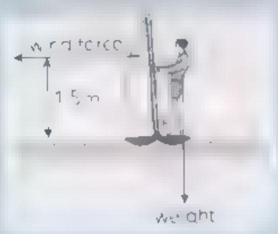
explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

8 The diagrams show a windsurfer pulling up the sail of a sailboard. The sail pivots where it joins with the board at point P.

a As the sail is pulled up from A to C, how does the force needed vary? Explain your answer. [2]

The windsurfer and the sailboard shown in the diagram below are in equilibrium.

b What does equilibrium mean? [1]



The windsurfer weighs 900 N. The wind is blowing with a force of 300 N. The windsurfer maintains equilibrium.

c Calculate how far to the right of the pivot the windsurfer has to move his centre of gravity. [2]

d What would the windsurfer need to do if the force of the wind decreased? Explain your answer. [2]

[Total: 7]

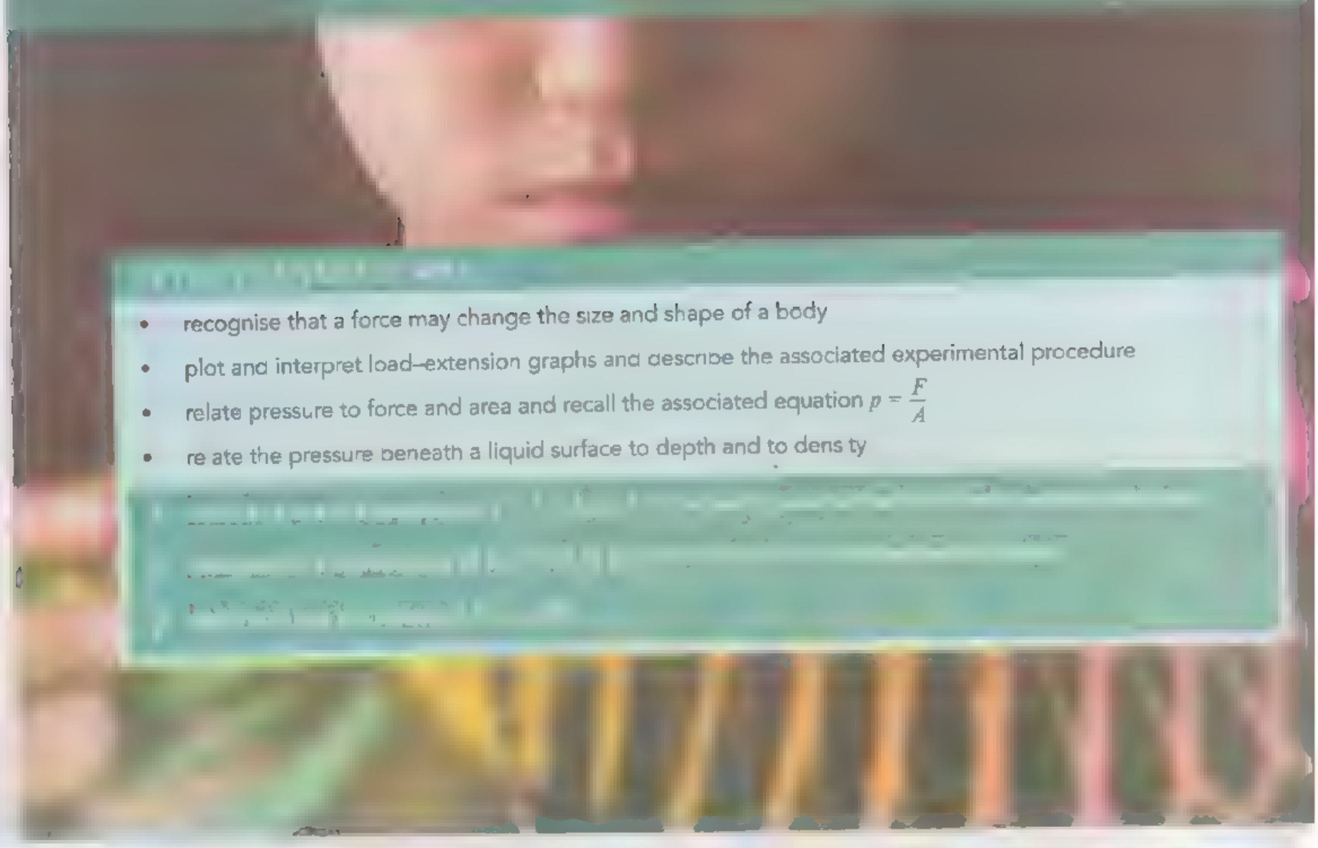
[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	Needs more work	Almost there	Confident to move on
Give everyday examples of a turning force.	4.1			
Understand that increasing force or distance from the pivot increases the moment of a force.	4.1			
Calculate the moment using the product force × perpendicular distance from the pivot.	4.2			
Apply the principle of moments to balancing a beam.	4.2			
Apply the principle of moments to different situations, including when there is more than one moment on either side of the pivot.	4.2			
Perform an experiment to find the centre of gravity of a piece of card.	4.3			
Describe how the location of the centre gravity affects stability.	4.3			

> Chapter 5

Forces and matter



- recognise that a force may change the size and shape of a body
- plot and interpret load–extension graphs and describe the associated experimental procedure
- relate pressure to force and area and recall the associated equation $p = \frac{F}{A}$
- relate the pressure beneath a liquid surface to depth and to density

GETTING STARTED

Figure 5.1 shows a pop-up popper toy. Figure 5.1a shows the popper in its natural state and Figure 5.1b shows it when it is turned inside out. Once turned inside out, a popper can jump several metres into the air. Using your knowledge of physics, explain how this can happen

Figure 5.1a: Rubber pop-up popper in its normal state **b:** When it has been turned inside out, just before springing back to its normal shape.

HOW THE MANTIS SHRIMP PUNCHES ABOVE ITS WEIGHT

Figure 5.2 shows a mantis shrimp. This marine creature can punch its prey (usually crabs) with a force of more than 700 N, over a thousand times its own bodyweight. It has hinged clubs at the front of its body called dactyls. They can reach speeds of 23 m/s in less than three milliseconds, more than 750 times the acceleration due to gravity. It achieves this by storing elastic potential energy in a part of its exoskeleton that is shaped like a saddle. This piece of exoskeleton behaves like a compressed spring or the rubber popper shown in Figure 5.1. Turning the popper inside out changes its shape. The shrimp uses its muscles to change the shape of part of its exoskeleton by transferring chemical potential energy into elastic potential energy. Humans achieve the same thing with a crossbow. Once enough energy has been stored, a latch can release it.

Figure 5.2: A mantis shrimp

Discussion questions

1 What weapons have humans developed that acts in the same way as the shrimp's dactyl? Can you think of other applications?

2 Could a 50 g mantis shrimp injure you? A punch from a mantis shrimp exerts the same force as the weight of a typical adult.

5.1 Forces acting on solids

Forces can change the size and shape of an object. They can stretch, squash, bend or twist it. Figure 5.3 shows the forces needed for these different ways of deforming an object. You could imagine holding a cylinder of foam rubber, which is easy to deform, and changing its shape in each of these ways.

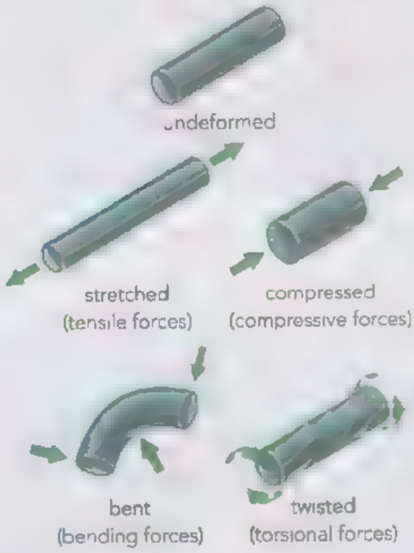


Figure 5.3: Forces can change the size and shape of a solid object. These diagrams show four different ways of deforming a solid object.

Foam rubber is good for investigating how things deform, because, when the forces are removed, it springs back to its original shape. Here are two more examples of materials that deform in this way:

Firstly, when a football is kicked, it is compressed for a short while (see Figure 5.4a). Then it springs back to its original shape as it pushes itself off the foot of the player who has kicked it. The same is true for a tennis ball when struck by a racket.

Secondly, bungee jumpers rely on the springiness of the rubber rope, which breaks their fall when they jump from a height (see Figure 5.4b). If the rope became permanently stretched, they would stop suddenly at the bottom of their fall, rather than bouncing up and down and gradually coming to a halt.

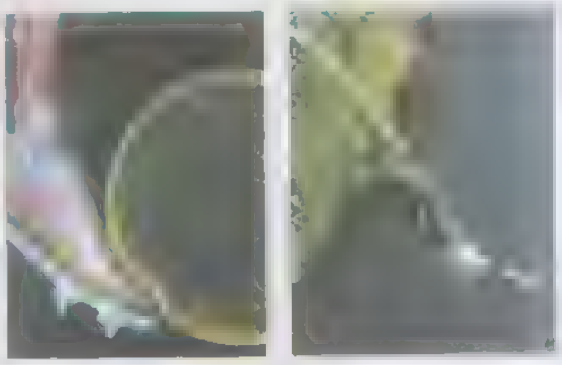


Figure 5.4a: This X-ray image shows how a football is compressed when it is kicked. It returns to its original shape as it leaves the player's boot. (This is an example of an elastic deformation.) The boot is also compressed slightly but, because it is stiffer than the ball, the effect is less noticeable. **b:** When the bungee cord reaches its maximum extension, it will return to its original length, pulling the bungee jumper upwards.

Some materials are less springy. They become permanently deformed when forces act on them.

- When two cars collide, the metal panels of their bodywork are bent.
- Gold and silver are metals that can be deformed by hammering them (see Figure 5.5). People have known for thousands of years how to shape rings and other ornaments from these precious metals.

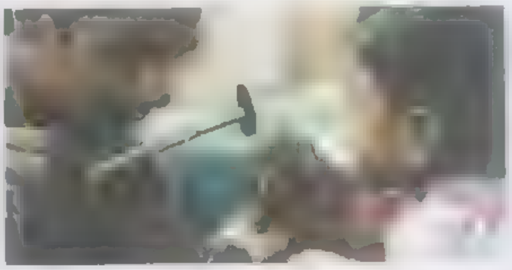


Figure 5.5: A Tibetan silversmith making a wrist band. Silver is a relatively soft metal at room temperature, so it can be hammered into shape without the need for heating.

5.2 Stretching springs

To investigate how objects deform, it is simplest to start with a spring. Springs are designed to stretch a long way when a small force is applied, so it is easy to measure how their length changes.

Figure 5.6 shows how to carry out an investigation on stretching a spring. The spring is hung from a rigid clamp, so that its top end is fixed. Weights are hung on the end of the spring — these are referred to as the **load**. As the load is increased, the spring stretches and its length increases.

Figure 5.6: Investigating the stretching of a spring

load: the force (usually weight) stretches an object (a spring)

Figure 5.7 shows the pattern observed as the load is increased in regular steps. The length of the spring increases (also in regular steps). At this stage the spring will return to its original length if the load is removed. However, if the load is increased too far, the spring becomes permanently stretched and will not return to its original length. It has been inelastically deformed.

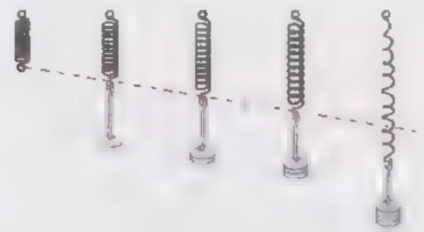


Figure 5.7: Stretching a spring. At first, the spring deforms elastically. It will return to its original length when the load is removed. Eventually, however, the load is so great that the spring is damaged

Extension of a spring

As the force stretching the spring increases, the spring gets longer. It is important to consider the increase in length of the spring. This quantity is known as the **extension**.

length of stretched spring = original length + extension

This means that, if you double the load that is stretching a spring, the spring will not become twice as long. It is the extension that is doubled.

extension: the increased length of an object (for example, a spring) when a load (for example, weight) is attached to it

Table 5.1 shows how to use a table with three columns to record the results of an experiment to stretch a spring. The third column is used to record the value of the extension, which is calculated by subtracting the original length from the value in the second column.

To see how the extension depends on the load, we draw a load–extension graph (Figure 5.8). You can see that the graph is in two parts.

- At first, the graph slopes up steadily. This shows that the extension increases in equal steps as the load increases.
- Then the graph curves. This happens when the load is so great that the spring has become permanently damaged. It will not return to its original length.

You can see the same features in Table 5.1. Look at the third column. At first, the numbers go up in equal steps. The last two steps are bigger.

Load / N	Length / cm	Extension / cm
0.0	24.0	0.0
1.0	24.6	0.6
2.0	25.2	1.2
3.0	25.8	1.8
4.0	26.4	2.4
5.0	27.0	3.0
6.0	27.6	3.6
7.0	28.6	4.6
8.0	29.5	5.6

Table 5.1: Results from an experiment to find out how a spring stretches as the load on it is increased

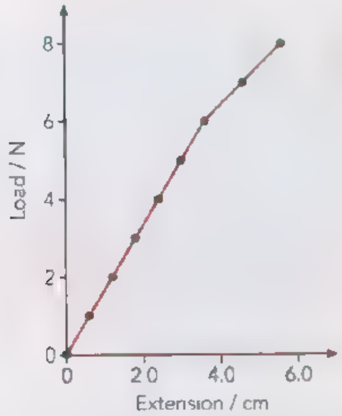


Figure 5.8: A load–extension graph for a spring, based on the data in Table 5.1

Questions

1. A piece of elastic cord is 75 cm long. When it is stretched, its length increases to 97 cm. What is its extension?
2. Table 5.2 shows the results of an experiment to stretch an elastic cord. Copy and complete the table, and draw a graph to represent this data (with load on the vertical axis).

Load / N	Length / cm	Extension / cm
0	75	0
2	81	
4	87	
6	93	
8	99	
10	105	
12	118	
14	135	
16	156	

Table 5.2

5.3 The limit of proportionality and the spring constant

The mathematical pattern of the stretching spring was first described by the British scientist Robert Hooke. He realised that, when the load on the spring was doubled, the extension also doubled. Three times the load gave three times the extension, and so on. This is shown in the graph in Figure 5.9. The graph shows how the extension depends on the load. At first, the graph is a straight line leading up from the origin. This shows that the extension is proportional to the load.

At a certain point, the graph curves and the line slopes up less steeply. This point is called the **limit of proportionality**. If the spring is stretched beyond this point, it will be permanently damaged. If the load is removed, the spring will not return all the way to its original, undeformed length.

limit of proportionality: up to this limit, the extension on a spring is proportional to load

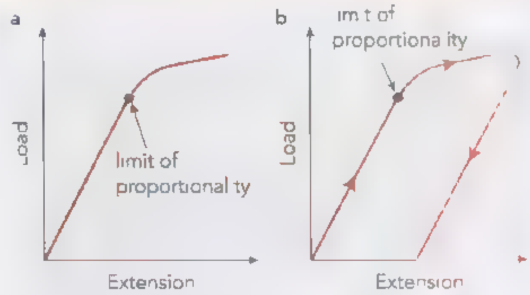


Figure 5.9a: A load–extension graph for a spring. Beyond the limit of proportionality, the graph is no longer a straight line, and the spring is permanently deformed. **b:** This graph shows what happens when the load is removed. The extension does not return to zero, showing that the spring is now longer than at the start of the experiment.

EXPERIMENTAL SKILLS 5.1

Investigating springs

Learning how different materials behave when a force is applied to them is very important if they are used to make something. The hull of the RMS Titanic was composed of mild steel plates held together by 3 million rivets. When the ship struck an iceberg in 1912 the force broke some of these rivets and this contributed to the ship sinking.

You will investigate how the extension of the spring changes as the load is increased and whether the extension on the spring is proportional to the load.

You will need

- eye protection
- clamp stand, boss and clamp
- spring
- hanger with slotted masses
- G-clamp
- ruler
- plumb line (a piece of thread with a lump of metal on the end).

Safety: You need to wear eye protection because there is a danger that the spring will fly into someone's eye if it breaks under tension. Place a mat on the floor beneath the masses so that, if the spring snaps, the masses will not damage the floor. Avoid standing on the mat because the masses may land on your feet if the spring snaps.

Getting started

1. Explain the purpose of:
   a. the G-clamp
   b. the plumb line.
2. Each slotted weight is 100 g. Calculate what load this represents.
3. Identify the independent (input) and dependent (output) variables.

Method

1. Set up the experiment as shown in Figure 5.10.

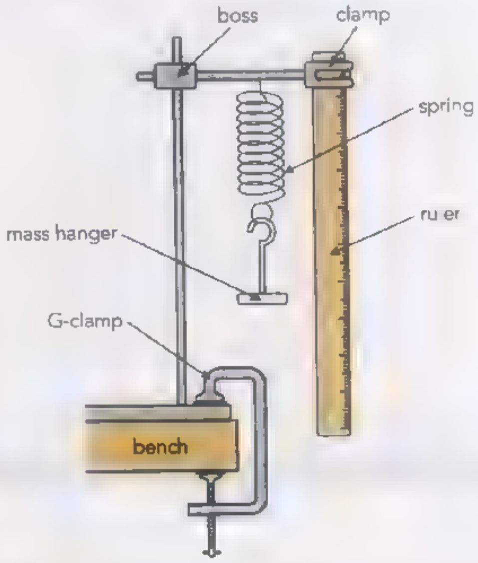


Figure 5.10: Apparatus for investigation

2. Arrange the ruler with zero at the top. This means that, as the steel spring stretches, the readings on the ruler increase.
3. Use the headings below to draw a results table. Remember to add more rows.

Load on hanger / N	Ruler reading / cm	Spring extension / cm	Does the spring return to original length when unloaded? Y/N

4. Attach your hanger to the bottom of the spring so that the spring hangs vertically.
5. Record the load as zero and record the reading on the ruler where it lines up with the bottom of the hanger.

CONTINUED

6 Add a slotted 100 g mass (equal to a load of 1.0 N) and record the new ruler reading where it lines up with the bottom of the hanger.

7 Remove the mass and record whether the steel spring returns to its original length.

8 Repeat steps 6 and 7, adding another 100 g mass each time until you have filled the table or the spring breaks

9 Remember, the extension is the difference between the length of the spring with the load attached and the original length when just the hanger was attached. To calculate the spring extension, subtract your ruler reading for a load of 0 N from all of your ruler readings. This means that the spring extension should be zero (0 cm) when the load is zero (0 N).

10 Plot a graph of load against extension (that is, extension on the horizontal axis). Include a title, axis labels and a line of best fit

Questions

1 Did your graph pass through the origin? If not, did you remember to correct for the original length of the spring?

2 How can you identify where on the graph the force on the steel spring is proportional to the load? What is the name of the point where this no longer happens to the spring and can you locate it on your graph?

3 What are the values for the load and extension corresponding to the limit of proportionality for your spring?

4 Did the spring continue returning to its original length beyond the limit of proportionality?

ACTIVITY 5.1

Elastic glass

Glass is brittle. It shatters once it reaches its limit of proportionality.

So, why can glass fibres (used in optic fibres and loft insulation) bend so easily without shattering? In this activity you will explain why you can bend glass fibres into a circle but a glass block will shatter if you try to bend it.

First, think about how you would approach this problem without the guidance that follows; make some notes of your ideas.

When you bend an object (such as a pencil eraser), one surface stretches and the opposite surface compresses (gets shorter). Take your textbook and measure the width of the bottom edge. It should be about 21 cm. Now bend it into the shape of an arch with the spine on the left-hand side as shown in Figure 5.11.

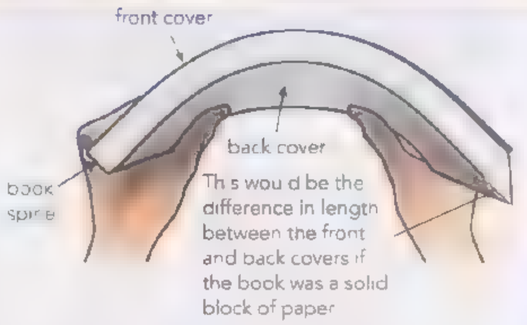


Figure 5.11: A textbook bent out of shape

You will see the book spine on the left-hand side is at right angles to both the front and back covers. The pages slide past each other so that the length of all the pages and the book covers have not changed. A solid block of paper (such as a stack of paper in its wrapper) is difficult to bend but, if you could bend it, the top surface would stretch and the bottom surface would compress and the right-hand edge would be at right-angles to the top and bottom surface as shown by the dotted red line to the right of the book. The little triangle of paper to the right of the dotted line would not be present. In this example, it would

result in an approximate difference of about 2 cm in length between the top and bottom surfaces. Half of this difference would be because the top surface stretched and the other half would be because the bottom surface compressed.

1 Either take measurements from Figure 5.11 or try the experiment yourself (in pairs). One person can hold and bend the book while the other person uses a set square to find where the dashed red line should be (no need to mark the book though). Use a ruler to measure the length indicated by the red double-headed arrow.

2 The extension (or compression) is half the length of the double headed arrow.

Engineers calculate strain, which is the extension divided by the original length. For the book in the picture this will be roughly 1 cm divided by 21 cm (~0.05 or 5%). Engineers have also worked out that different materials have different breaking strains. A glass fibre has a breaking strain of about 2%.

The breaking strain of ordinary glass is much lower than this, probably because it has microscopic (tiny) imperfections where stress tends to concentrate.

3 Would glass as thick as your book shatter if bent through the angle shown in Figure 5.11?

4 Calculate the extension (or compression) for an individual page. You learned how to work out the thickness of a single page in Chapter 1. How does extension vary with the thickness of the object that is being bent out of shape?

5 Would glass as thick as a page in your book shatter if bent through the angle shown in Figure 5.11?

Other things to think about

1 What is the relationship between the length of the double-headed arrow and the thickness of the book?

2 What is the relationship between the length of the double-headed arrow and how much the book is bent?

The behaviour of the spring is represented by the graph in Figure 5.10c and can be described as:

The extension of a spring is proportional to the load applied to it, provided the limit of proportionality is not exceeded.

This is also known as Hooke's law. We can write the behaviour of a spring as an equation:

$F = kx$

In this equation, F is the load (force) stretching the spring, k is the **spring constant** of the spring, and x is the extension of the spring. The spring constant is defined as the force per unit of extension, which is obvious when Hooke's law is expressed in terms of k:

$$k = \frac{F}{x}$$

spring constant = $\frac{\text{force}}{\text{unit extension}}$

$$k = \frac{F}{x}$$

The spring constant is a measure of the 'stiffness' of the spring: the stiffer the spring, the bigger the load required to change its length and the steeper the gradient when load is plotted against extension (i.e. with extension on the horizontal axis).

spring constant: the constant of proportionality; the measure of the stiffness of a spring

A spring has a spring constant k = 20 N/cm. What load is needed to produce an extension of 2.5 cm?

Step 1: Write down what you know and what you want to find out.

spring constant k = 20 N/cm

extension = 2.5 cm

load F = ?

Step 2: Write down the equation linking these quantities, substitute values and calculate the result.

$F = kx$

F = 20 N/cm × 2.5 cm = 50 N

Answer

A load of 50 N will stretch the spring by 2.5 cm.

How rubber behaves

A rubber band can be stretched in a similar way to a spring. As with a spring, the bigger the load, the bigger the extension. However, if the weights are added with great care, and then removed one by one without releasing the tension in the rubber, the following can be observed.

- The graph obtained is not a straight line. Rather, it has a slightly S-shaped curve. This shows that the extension is not exactly proportional to the load.
- Eventually, increasing the load no longer produces any extension. The rubber feels very stiff. When the load is removed, the graph does not come back exactly to zero.

Hooke and springs

Why was Robert Hooke so interested in springs? Hooke was a scientist, but he was also a great inventor. He was interested in springs for two reasons.

- Springs are useful for making weighing machines, and Hooke wanted to make a weighing machine that was both very sensitive (to weigh very light objects) and very accurate (to measure very precise quantities).
- He also realised that a spiral spring could be used to control a clock or even a wristwatch.

Figure 5.12 shows a set of diagrams drawn by Hooke, including a long spring and a spiral spring, complete with pans for carrying weights. You can also see some of his graphs.

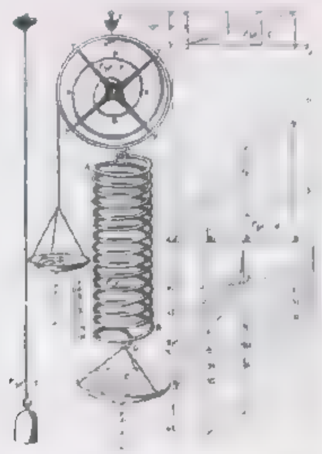


Figure 5.12 Robert Hooke's diagrams of springs

For scientists, it is important to publish results so that other scientists can make use of them. Hooke was very secretive about some of his findings because he did not want other people to use them in their own inventions. For this reason, he published some of his findings in code. For example, instead of writing his law of springs as given above, he wrote ceiiinosssttuv. Later, when he felt that it was safe to publish his ideas, he revealed that this was an anagram of a sentence in Latin. Decoded [illegible] *Ut tensio, sic vis*. In English, this is 'As the [illegible] increases, so does the force.' In other words the extension is proportional to the force producing it. You can see Hooke's straight-line graph in Figure 5.

Questions

3 A spring requires a load of 7.5 N to increase its length by 5.0 cm. What load will give it an extension of 12 cm?

4 A spring has an unstretched length of 13.0 cm. Its spring constant, k is 7.0 N/cm. What load is needed to stretch the spring to a length of 18.0 cm?

5 The results of an experiment to stretch a spring are shown in Table 5.3. Use the results to plot a load–extension graph. On your graph, mark the limit of proportionality and state the value of the load at that point.

Load / N	Length / m
0.0	1.396
2.6	1.422
5.3	1.448
7.9	1.475
10.6	1.501
13.2	1.536
15.9	1.579

Table 5.3

Think back to Activity 5.1. This was an example of a thought experiment. Great scientists like Albert Einstein have used this approach to make huge progress in science.

Did you need the guidance? If so, was it helpful?

When bending an object, you compress it on the side that gets shorter and stretch (or extend) it on the other side.

Could you imagine what was happening? When you roll one sheet of paper into a cylinder, the inside circumference and outside circumference are nearly the same length: there has been very little stretching (extension) or compression. This is the same as the glass fibre. Can you see that, by making the paper very much thicker, the difference in length between the inner and outer circumferences would get bigger and so would the extension and compression? Glass is quite brittle so stretching it too much will make it shatter.

Can you think of ways of developing this thinking skill and practising it in the next two activities in this chapter and beyond?

5.4 Pressure

If you dive into a swimming pool, you will experience the pressure of the water on you. It provides the upthrust, which pushes you back to the surface. The deeper you go, the greater the pressure acting on you. Submarines and marine exploring vehicles (Figure 5.13) must be designed to withstand very great pressures. They have curved surfaces, which are much stronger under pressure, and they are made of thick metal.

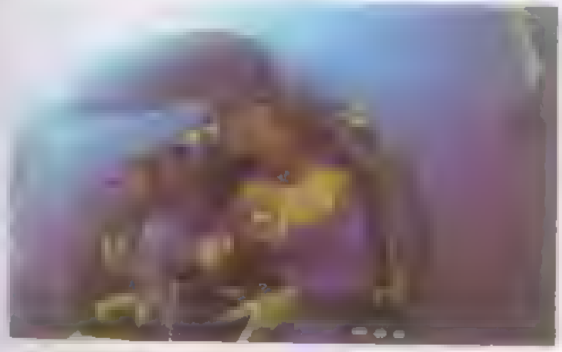


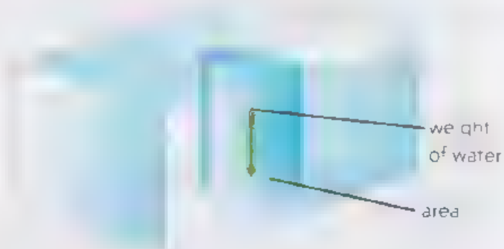
Figure 5.13: This underwater exploring vehicle is used to carry tourists to depths of 600 metres, where the pressure is 61 times that at the surface. The design makes use of the fact that spherical and cylindrical surfaces stand up well to pressure. The viewing window is made of acrylic plastic and is 9.5 cm thick.

This pressure comes about because any object under water is being pressed down on by the weight of water above it. The deeper you go, the greater the amount of water pressing down on you (see Figure 5.14a). In a similar way, the atmosphere exerts pressure on us, although we are not normally conscious of this. The Earth's gravity pulls it downwards, so that the atmosphere presses downwards on our heads. Mountaineers climbing to the top of Mount Everest rise through two-thirds of the atmosphere, so the pressure is only about one-third of the pressure down at sea level. There is much less air above them, pressing down.

The pressure caused by water is much greater than that caused by air because water is much denser than air. Figure 5.14b shows how a dam is designed to withstand the pressure of the water behind it. Because the pressure is greatest at the greatest depth, the dam must be made thickest at its base.

In a fluid such as water or air, pressure does not simply act downwards – it acts equally in all directions. This is because the molecules of the fluid move around in all directions, causing pressure on every surface they collide with.

a



b

Figure 5.14a: Pressure is caused by the weight of water (or other fluid) above an object. **b:** This dam is thickest near its base, because that is where the pressure is greatest.

Drinking through straws and breathing through snorkels

1. When you drink through a straw, are you pulling the liquid up the straw or is atmospheric pressure pushing the liquid up the straw? Try to explain what is going on.
2. Try this with family or friends. Drink through two straws, with the end of one straw below the surface of the liquid and the end of the other straw above the liquid surface. Explain why you or your friends fail to draw up any liquid through either straw.
3. We can modify (bend) a straw and use it to breathe under water. Figure 5.15a shows someone using a snorkel. Normally, snorkelers hold their breath and dive to explore deeper under water. But could someone just breathe from a longer snorkel? Is there a practical limit to the length that a snorkel can be or the depth you can breathe from one? If so, try to explain why.
4. An elephant can swim under water and use its trunk as a snorkel (Figure 5.15b). Use the Internet to research how an elephant can breathe when deeper in the water than we can and present your work on an A4 or A3 poster.

Figure 5.15a: A snorkeler **b:** Elephants can use their trunks as snorkels to help them breathe and can swim deeper than humans.

5.5 Calculating pressure

A large force pressing on a small area gives a high pressure. We can think of pressure as the force per unit area acting on a surface, and we can write an equation for pressure, as shown:

$$\text{pressure} = \frac{\text{force}}{\text{area}} \qquad p = \frac{F}{A}$$

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

$$p = \frac{F}{A}$$

Now let us consider the unit of pressure. If force, F, is measured in newtons (N) and area, A, is in square metres (m^2), then pressure, p, is in newtons per square metre (N/m^2). In the SI system of units, this is given the name pascal (Pa). It is equivalent to one newton per square metre (1 N/m^2).

pressure the force acting per unit area at right angles to a surface

pascal the SI unit of pressure, equivalent to one newton per square metre, 1 Pa = 1 N/m^2 = 1 Pa

Stiletto heels have a very small surface area. [illegible] is an Italian word meaning a small and [illegible] dagger.) Such narrow heels can damage [illegible] dance halls often have notices requiring [illegible] such heels to be removed.

Calculate the pressure exerted by a dancer [illegible] 600 N standing on a single heel of area 1 cm^2. The surface of the dance floor is broken by pressures over 5 million pascals (5.0 MPa). Will it be d[illegible] the dancer?

Step 1: To calculate the pressure, we need to k[illegible] force and the area on which the force [illegible]

force F = 600 N

area A = 1 cm^2 = 0.0001 m^2 = [illegible] m^2

Step 2: Now we can calculate the pressure p

$$= \frac{600\ \text{N}}{0.0001\ \text{m}^2}$$

$$= 6\,000\,000\ \text{Pa}$$

$$= 6.0\ \text{MPa}$$

Answer

The pressure is 6.0×10^6 Pa, or 6.0 MPa. This is more than the minimum pressure needed to break the surface of the floor, so it will be damaged.

Questions

6 Write down an equation that defines pressure

7 What is the SI unit of pressure?

8 Which exerts a greater pressure, a force of 200 N acting on 1.0 m², or the same force acting on 2.0 m²?

9 What pressure is exerted by a force of 50 000 N acting on 2.5 m²?

10 A swimming pool has a level, horizontal, bottom. Its dimensions are 25.0 m by 5.0 m. The pressure of the water on the bottom is 15 000 Pa. What total force does the water exert on the bottom of the pool? What is the weight of water?

11 An elephant has a mass of 5000 kg. The area of an elephant's foot is 0.13 m².

A woman has a mass of 60 kg. The area of her stiletto heel is 25 mm².

- a State the equation linking weight, mass and g. Use the equation to calculate the weights of the elephant and the woman.
- b State the equation that links (solid) pressure, force and area.
- c Calculate the pressures exerted by the elephant and woman. (Hint: Remember that weight is a force and that you need to convert the area of the stiletto heel into m².)
- d Use the pressure values you calculated to suggest why the women might cause more damage to a floor than an elephant.

Pressure, depth and density

We have seen that the deeper one dives into water, the greater the pressure. Pressure p is proportional to depth h (we use the letter h, for height). Twice the depth means twice the pressure. Pressure also depends on the density ρ of the material (where ρ is the Greek letter rho). If you dive into mercury, which is more than ten times as dense as water, the pressure will be more than ten times as great.

We can write an equation for the change in pressure at a depth h in a fluid of density ρ:

change in pressure = density × acceleration due to gravity × depth

KEY EQUATION

change in pressure = density × acceleration due to gravity × depth

$$\Delta p = \rho g \Delta h$$

Atmospheric stopper

Fill a container, such as a bottle or beaker, with water to the brim (top).

Place a piece of stiff card on top of the bottle or beaker so that it more than covers the opening (in other words, it is wider than the opening). You could use a table tennis ball instead of card, if the bottle has a very narrow neck.

Ensure that you do the next step over a sink. While holding the card firmly to the top of the container, turn the container upside down and slowly remove your hand from the card. The water should stay in the container.

Explain why this happens. Think about what forces are acting on the card. What is the tallest column of water you could use before the 'trick' no longer works?

The activities in this chapter asked you to imagine what is happening. It can be helpful for scientists to visualise (imagine something in their mind). Can you think of ways that you can develop your scientific imagination?

Calculate the pressure on the bottom of a swimming pool that is 2.5 metres deep. How does the pressure compare with atmospheric pressure, 10^5 Pa (100 000 Pa)? The density of water = 1000 kg/m³.

Step 1: Write down what you know, and what you want to know.

$\Delta h = 2.5$ m

$\rho = 1000$ kg/m³

$g = 10$ N/kg

$\Delta p = ?$

Step 2: Write down the equation for pressure, substitute values and calculate the answer.

$\Delta p = \rho g \Delta h = 1000$ kg/m³ × 10 N/kg × 2.5 m

$= 2.5 \times 10^4$ Pa

Answer

This is one quarter of atmospheric pressure. We live at the bottom of the atmosphere. There is about 10 km of air above us, pressing downwards on us; that is the origin of atmospheric pressure.

Questions

12 The density of water is 1000 kg/m³. Calculate the pressure due to the water on a diver when he is 25 metres under the surface.

13 Figure 5.16 shows a tank that is filled with oil. The density of the oil is 920 kg/m³.

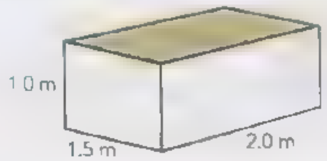


Figure 5.16: A tank filled with oil

- **a** Calculate the volume of the tank.
- **b** Calculate the weight of the oil in the tank.
- **c** The pressure on the bottom of the tank is caused by the weight of the oil. Calculate the pressure using

  $p = \frac{F}{A}$

- **d** Now calculate the pressure using

  $\Delta p = \rho g \Delta h$

  Do you find the same answer as in part **c**?

14 Atmospheric pressure is 100 000 Pa. The roof of a building has an area of 50 m².

- **a** What force does the atmosphere exert down on the roof?
- **b** Explain why the roof does not collapse.
- **c** What would happen to the roof if it were possible to remove all of the air from inside the building? Explain your answer.

15 Calculate the depth of the pool in question 10. Assume the density of water = 1000 kg/m³ and g = 10 N/kg.

PROJECT

Under pressure

Develop a resource about pressure for a future IGCSE class.

How to present your work

Choose the medium you think is most suitable for your work (such as a PowerPoint presentation or podcast).

As far as possible, produce your own informative drawings, photographs or video clips (which should last for less than one minute).

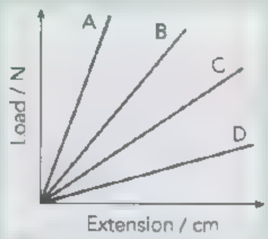
List all the sources of your information (websites, books, television documentaries, and so on) with enough details for other people to find the sources.

What you need to include

1. Introduce each of the two equations you have met in this chapter at the appropriate point in your resource and, for each equation, include an example question with its solution.
2. Describe a situation in which pressure is deliberately increased (by increasing the force or reducing the area).
3. Describe a situation in which pressure is deliberately reduced (by increasing the area).
4. Choose one of the following:
   - Explain why the collapsing can experiment works using the first pressure equation you met in this chapter. Unless this has been demonstrated in class, you might need to search for it on the Internet.
   - Explain why pressure increases with increasing depth in a fluid and therefore why a dam must be made thicker (or wider) in cross-section with increasing depth.
   - Explain how a hydraulic braking system in a car works. It is important to emphasise that pressure in a fluid does not simply push down from above. It pushes from all directions.

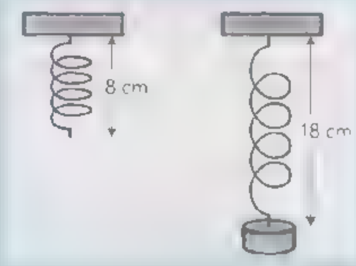
Forces can change the size and shape of an object.
An object (for example, a spring) will stretch when a load is attached to it.
To calculate the extension of a spring for a given load, its original length must be subtracted from its new length.
Stretching a spring beyond its limit of proportionality permanently deforms it and it will not return to its original size and shape
The extension on a spring is proportional to the load applied to the spring until the spring reaches the limit of proportionality
On a load–extension graph, the extension on a spring is proportional to the load applied to the spring where the line is straight.
The graph starts to curve at the limit of proportionality; beyond this point, the extension on a spring is not proportional to the load applied to the spring.
The spring constant is defined as the force per unit extension, $k = \frac{F}{x}$.
The bigger the spring constant, the more difficult it is to stretch the spring. We say that the object is stiffer
Rubber returns to its original size and shape unless the load is increased after it has stopped stretching.
Pressure is the force (for example, weight) per unit area (perpendicular to the surface)
Pressure in a fluid (liquid or gas) is caused by the weight of fluid above it.
Because the pressure is greatest at the greatest depth, a dam is thickest at its base.
For pressure in a fluid, it is more usual to use the equation change in pressure = density × gravitational field strength × depth, $\Delta p = \rho g \Delta h$.

1 Look at the graph. Which material is the stiffest? **[1]**



CONTINUED

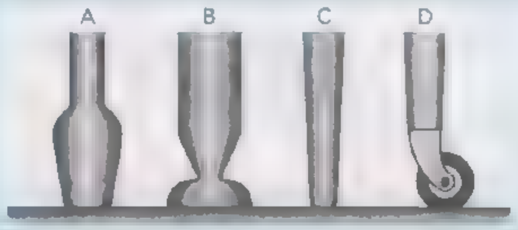
2 This spring obeys Hooke's law and stretches from 8 cm to 18 cm when a force of 20 N is applied.



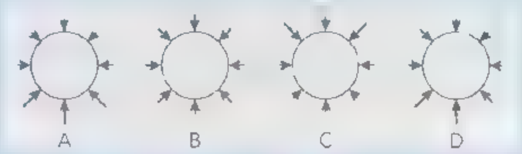
What is its total length, in cm, when a force of 30 N is applied? [1]

A 23 **B** 26 **C** 27 **D** 28

3 Heavy furniture sometimes marks the floor on which it stands. Four tables of the same weight each have four legs. The figure shows part of a leg from each table. Which table is least likely to mark the floor? [1]



4 Which diagram shows the pressure acting on the submarine that is not moving? [1]



What causes the pressure of air at the Earth's surface? [1]

[illegible]

At the Earth's surface, atmospheric pressure is 10^5 Pa and the density of air is $1.3\ kg/m^3$. Use this information to calculate the height (or depth) of the atmosphere.

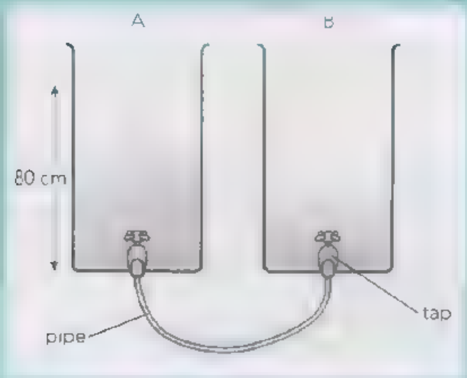
[illegible] the atmosphere. [1]

[Total: 4]

state: express in clear terms

calcula[illegible]: work out from given facts, figures or information

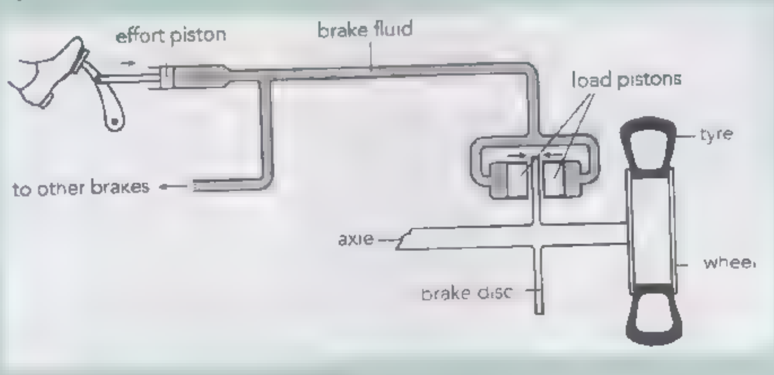
suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals / put forward considerations



set out purposes or reasons / make the relationships between things evident / provide why and / or how and support with relevant evidence

CONTINUED

7 Car braking systems multiply forces. In the diagram below, there are three pistons: one effort piston and two load pistons.



a The effort piston has an area of 2.0 cm^2. The driver exerts a force of 50 N on the effort piston. What is the pressure of the brake fluid? [2]

b This pressure is the same everywhere in the brake fluid, including at the load pistons. The load pistons have a total area of 40 cm^2. Calculate the force at the brake disc. [2]

[Total: 4]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible] more work	[illegible]	[illegible]
Recall that forces can change the size and shape of an object	5.1			
Plot and interpret load–extension graphs and describe the associated experimental procedure	5.2			
Recall how to calculate the extension of a spring for a given load	5.2			
Recall what happens to a spring if it is stretched beyond its limit of proportionality	5.2			
Recall the equation for determining the spring constant.	5.3			
Identify the limit of proportionality on a load–extension graph and where on the graph the extension is proportional to the load	5.3			
Understand the significance of the spring constant and recognise how an object with a different spring constant would appear on a load–extension graph	5.3			

CONTINUED

I can	[illegible]	[illegible]	[illegible]	[illegible]
Recall the equation that relates pressure, force and area.	5.5			
Recall what causes the pressure to increase with increasing depth into water	5.5			
Recall and use the equation for pressure in a fluid.	5.5			

> Chapter 6

Energy stores and transfers

- identify changes in different energy stores
- recognise different energy transfers and interpret energy flow diagrams
- understand the meaning of energy efficiency
- apply the principle of conservation of energy

Work with a classmate to describe the energy transfers that are taking place in each diagram.

What do you already know about energy?

With a classmate, draw an energy mind map to include everything you know about this topic, including the principle of conservation of energy.

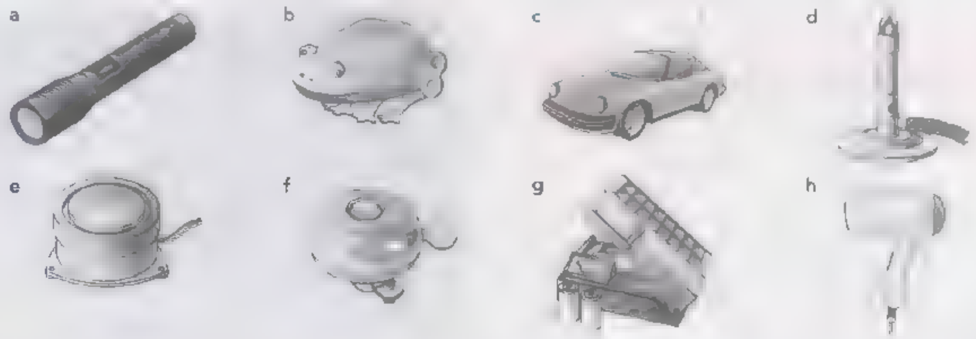


Figure 6.1a: Flashlight switched on **b:** Wound up toy **c:** Moving radio-controlled car **d:** Bunsen burner **e:** Loudspeaker in use. **f:** Ringing bicycle bell **g:** Solar-powered battery. **h:** Hair dryer

People have different opinions about comets, both good and bad. Some people think comets are 'dirty snowballs' that brought water to our planet which allows us to live. However, along with asteroids, comets also threaten life on Earth. For example, the impact of an asteroid or comet wiped out the dinosaurs 66 million years ago. It is not surprising that comets used to be seen as warnings of disaster (Figure 6.2). However, thanks to physics, comets are now less mysterious and we can predict their paths. Astronomers working for Spaceguard search the skies, looking for and tracking objects (including comets) that might collide with the Earth.

Figure 6.2: The engraving that shows Halley's Comet in 1066. The Monk of Malmesbury sees it as a warning of the Norman Conquest, when the Normans invaded England.

Comets can cross our path (and collide with Earth) because their orbits are highly elliptical (shaped like squashed circles). The speed of Earth in its orbit around the Sun is nearly constant because its orbit is nearly circular. The speed of a comet changes. As it moves closer to the Sun, more of the comet's gravitational potential energy is transferred into kinetic energy, so it speeds up. As it gets further away from the Sun, some of its kinetic energy transfers into gravitational potential energy, and it slows down.

Discussion questions

1 When was the Earth's last major collision with an asteroid or comet and what happened?

2 Describe a system on Earth where energy transfers from gravitational potential energy to kinetic energy and back again.

3 Describe the energy transfers when you throw a ball into the air and relate this to the energy transfers for a comet orbiting the Sun.

6.1 Energy stores

Energy can be divided into energy stores and energy transfers. Energy, and energy transfers, are involved in all sorts of activities. We will look at two examples and see how we can describe them in terms of energy. We need to have the idea of stores of energy.

energy: quantity that must be changed or transferred to make something happen

Example 1: running

At the start of a race, you are stationary, waiting for the starter's pistol. Energy is stored in your toned-up muscles, ready to be released. As you set off, the energy from your muscles gets you moving. If you are running a marathon, you will need to make use of the energy in the longer-term stores of the fatty tissues of your body.

The energy transfers involved are shown in Figure 6.3. Your muscles store chemical energy. The energy is stored by chemicals in your muscles, ready to be released at a moment's notice. Your muscles start you moving, and you then have kinetic energy. Running makes you hot. This tells us that some of the energy released in your muscles is wasted as thermal energy, rather than becoming useful kinetic energy. Fitness training helps people to reduce this waste.

Figure 6.3a: At the start of a race, the runner's muscles are stores of chemical energy. **b:** As the runner starts to move, chemical energy is transferred to kinetic energy and thermal energy.

Example 2: switching on a light

It is evening, and the daylight is fading. You switch on the light. Your electricity meter starts to turn a little faster, recording the fact that you are drawing more energy from the distant power station.

The energy changes involved are shown in Figure 6.4. Electricity is useful because it brings energy, available at the flick of a switch. We can think of the energy being transferred electrically. In the light bulb, this energy is transferred by light. Every light bulb also produces thermal energy.

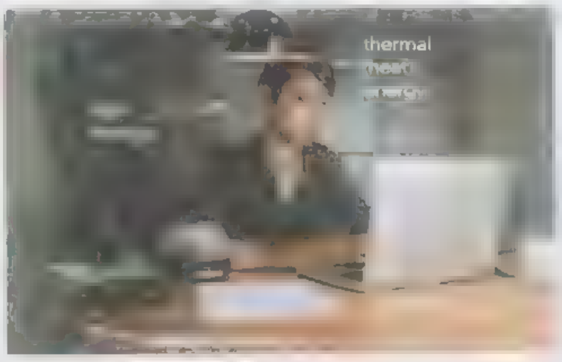


Figure 6.4: Switching on the light requires a supply of electricity. In the light bulb, electrical energy is transferred by light and heating.

Naming energy

Example 1 and Example 2 highlight some of the various energy stores and transfers. We will now take a brief look at examples of these.

A moving object has kinetic energy. The faster an object moves, the greater its kinetic energy. We know this because we need to transfer energy to an object to get it moving

If you lift an object upwards, you give it gravitational potential energy (g.p.e.). The higher an object is above the ground, the greater its g.p.e. If you let the object fall, you can get the energy back again. This is exploited in many situations. The water stored behind a hydroelectric dam has g.p.e. As the water falls, it can be used to drive a turbine to generate electricity. A grandfather clock has weights that must be pulled upwards once a week. Then, as they gradually fall, they drive the pendulum to operate the clock's mechanism.

kinetic energy: the energy store of a moving object

gravitational potential energy (g.p.e.): the energy store of an object raised up against the force of gravity; more generally, it is the distance between particles or bodies

Fuels such as coal or petrol (gasoline) are stores of chemical energy. We know that a fuel is a store of energy because, when the fuel burns, the stored energy is released, usually as heat and light There are many other stores of chemical energy (see Figure 6.5). As Figure 6.3 shows, energy is stored by chemicals in our bodies. Batteries are also stores of energy. When a battery is part of a complete circuit, the chemicals start to react with one another and an electric current flows. The current carries energy to the other components in the circuit.

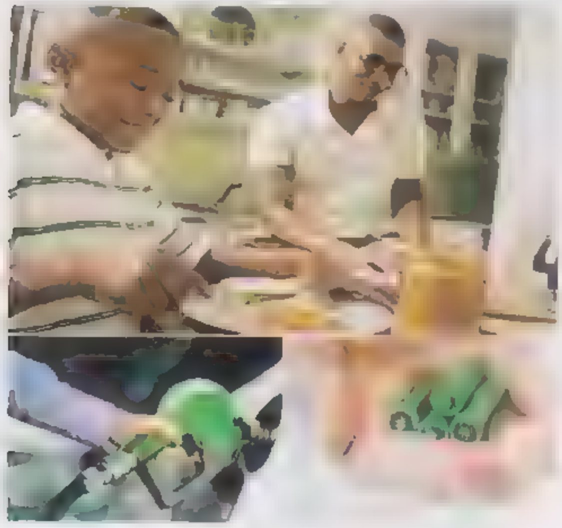


Figure 6.5: Some stores of chemical energy – bread and peanut butter, petrol, batteries Our bodies have long-term stores of energy in the form of fatty tissues.

An electric current is a good way of transferring energy from one place to another. When the current flows through a component such as a heater, it gives up some of its energy.

Uranium is an example of a nuclear fuel, which is a store of nuclear energy. All radioactive materials are also stores of nuclear energy. In these substances, the energy is stored in the nucleus of the atoms – the tiny positively charged core of the atom. A nuclear power station is designed to release the nuclear energy stored in uranium

If you stretch a rubber band, it becomes a store of strain energy The band can give its energy to a paper pellet and send it flying across the room. Strain energy is the energy stored by an object that has been stretched or squashed in an elastic way (so that it will spring back to its original dimensions when the stretching or squashing forces are removed). For this reason, it is also known as elastic energy. The metal springs of a car are constantly storing and releasing elastic energy as the car travels along, so that the occupants have a smoother ride. A wind up clock stores energy in a spring, which is the energy source needed to keep its mechanism operating.

If you heat an object so that it gets hotter, you are giving energy to its atoms. The energy stored in a hot object is called internal energy. We can picture the atoms of a hot object jiggling rapidly about they have a lot of energy This picture is developed further in Chapter 9.

If you get close to a hot object, you may feel thermal energy coming from it This is energy travelling from a hotter object to a colder one. The different ways in which this can happen are described in Chapter 11.

It is important not to confuse internal energy and thermal energy. The internal energy of an object is the total kinetic and potential energies of the particles it is made of The internal energy of an object will be higher if these particles are moving faster (higher kinetic energy) or they are further apart (bigger potential energy). Heating an object (giving it more thermal energy) raises its internal energy and this can raise its temperature or change its state (from water to steam, for example) Steam has more internal energy than boiling water even though they are at the same temperature. The particles (water molecules) in steam have more potential energy than water molecules in boiling water because they are further apart. Thermal energy spreads out from a hot object.

Very hot objects glow brightly. They are transferring energy by light Light radiates outwards all around the hot object.

Another way in which energy can be transferred to an object's surroundings is by sound. An electric current transfers energy electrically to a loudspeaker. Energy is transferred to the surroundings as sound and thermal energy (see Figure 6.6).

KEY WORDS

chemical energy: energy stored in bonds between atoms that can be released when chemical reactions take place

nuclear energy: energy stored in the nucleus of an atom

strain energy/elastic energy: energy stored in the changed shape of an object

internal energy: the energy of an object; the total kinetic and potential energies of its particles

thermal energy: energy transferred from a hotter place to a colder place because of the temperature difference between them

Energy stores, energy transfers

Imagine that energy is like money. The amount of money you have determines what you can buy. The amount of energy you have determines what you can do.

Let us imagine that the amount of money I have is fixed (I cannot earn any or spend it) Some of my money is stored in my bank account, some in my wallet and some down the back of my sofa. I can transfer (move) money between these stores but the total money I have does not change

Energy stores are potential energy. Energy can also transfer between stores, but the total amount of energy never changes. So, energy can be stored or it can be transferred

Table 6.1 lists energy under two headings: energy stores and energy transfers.

Energy stores	Energy transfers
kinetic energy (k.e.)	electrical
gravitational potential energy (g.p.e.)	thermal (heat)
chemical energy	radiation (such as light)
elastic (strain) energy	mechanical (such as sound, which is a way of transferring vibrational kinetic energy)
nuclear energy	
internal energy	
electrostatic energy	

Table 6.1: Energy can be classified as stores or transfers.

Figure 6.6: At a major rock concert, giant loudspeakers transfer sound to the audience. Extra generators may have to be brought on to the site to act as a source of energy to power the speaker systems. Much of the energy supplied is wasted as thermal energy, because only a fraction of the energy is transferred by sound.

Figure 6.7: When a catapult fires a ball, energy is transferred from the elastic store of the catapult to the kinetic store of the ball. If the ball is fired vertically upwards, energy from the kinetic energy store is transferred to the g.p.e. store, until there is nothing left in the kinetic energy store. The ball stops moving upwards and starts falling, with energy transferring from the gravitational store back to the kinetic store

Energy can be transferred from one store to another, even within the same object.

For example, when you climb a hill, you are transferring energy from your chemical store to your gravity (or g.p.e.) store. Here are four different ways in which energy can be transferred:

- By a force (mechanical working). If you lift something, you give it gravitational potential energy – you provide the force that lifts it. Alternatively, you can provide the force needed to start something moving – you give it kinetic energy. Firing a catapult (Figure 6.7) is another example of a mechanical transfer. When energy is transferred from one object to another by means of a force, we say that the force is **doing work**. This is discussed in detail in Chapter 8.
- By heating (thermal working). We have already seen how thermal energy spreads out from hot objects. No matter how good the insulation, energy is transferred from a hot object to its cooler surroundings. This is discussed in detail in Chapter 11.
- By radiation (light). Light reaches us from the Sun. That is how energy is transferred from the Sun to the Earth. Some of the energy is also transferred as infrared and ultraviolet radiation. These are examples of **electromagnetic radiation** (see Chapter 15).
- By electrical currents (electrical working). An electric current is a convenient way of transferring energy from place to place. The electricity may be generated in a power station many kilometres away from where the energy is required. Alternatively, an electrical current transfers energy from the chemical energy store of a flashlight battery to the internal energy of a bulb. This increased internal energy store of the bulb is transferred to the surroundings via light radiation. This is covered in Chapter 18.

doing work: transferring energy by means of a force

electromagnetic radiation: energy that is transferred using electromagnetic waves

Questions

1. What name is given to the energy of a moving object?
2. What do the letters g.p.e. stand for? How can an object be given g.p.e.?
3. What energy is stored in a stretched spring?
4. Explain why steam is likely to lead to a more serious skin burn than boiling water.
5. Look at the list of energy stores shown in Table 6.1. For each, give an example of an object or material that stores this energy.
6. Look at the physical clues in the left column of Table 6.2 and write down which energy store is changing.

Physical clue	Which energy store is changing?
material changing shape	
object changes speed	
chemical reaction	
change of temperature	
nuclear fission or fusion	
distance between objects changes	

Table 6.2

6.2 Energy transfers

We have already mentioned several examples of energy transfers. Now we will look at a few more and think a little about how energy is transferred between stores during events and processes, and how these transfers can be represented by energy flow diagrams.

Striking a match is an example of an **event** while burning is a **process**. An event is something that happens or takes place, often at a specific time and place. A process is a series of actions or steps, often taking place over a long period of time. Climbing a mountain would be an example of a process, while falling over would be an event. Sometimes, it is difficult to tell the difference between an event and a process. The important thing to remember is that energy is only transferred or changed during events and processes: in other words, when something happens.

event: something that happens or takes place, often at a specific time and place

process: a series of actions or steps, often taking place over a long period of time

Figure 6.8 shows scuba divers using flashlights during a dive at night. The transfer of energy to the lightbulbs is a process. The chemical energy stored in the battery is transferred electrically through the wires to the light bulbs, which increases its store of internal energy. The lamp transfers (useful) energy by light to the surroundings as well as by heating, which is wasted. The divers would be in serious danger if their flashlight ran out of charge. They cannot replace or recharge their batteries under water. They need their flashlights to be efficient so that most of the chemical energy is transferred usefully by light and very little is wasted as thermal energy. A more efficient flashlight will produce light for a longer time.

The energy stores and transfers in a flashlight can be represented by the flow diagram in Figure 6.9. The blue boxes show the energy stores (and where those stores are) and the green boxes with arrows show the energy transfers.

Figure 6.8: Divers using flashlights.

Figure 6.10: Mars Curiosity rover.

A device called a radioisotope thermoelectric generator (RTG) is a source of energy used in space probes. The Apollo missions and the Mars Curiosity rover used them (Figure 6.10). They are ideal for remote places where batteries, generators or solar cells are not practical. Also, because the devices have no moving parts, they are more reliable than alternatives and require very little maintenance.

The energy transfers in an RTG are another example of a process. In an RTG, a container seals a radioactive source (usually plutonium-238). The radioactive source produces thermal energy, raising the internal energy of the fuel. Thermocouples pass through the walls of the container, with the inner end of each thermocouple kept hot by the fuel while the outer end is connected to a heat sink so that it stays cold.

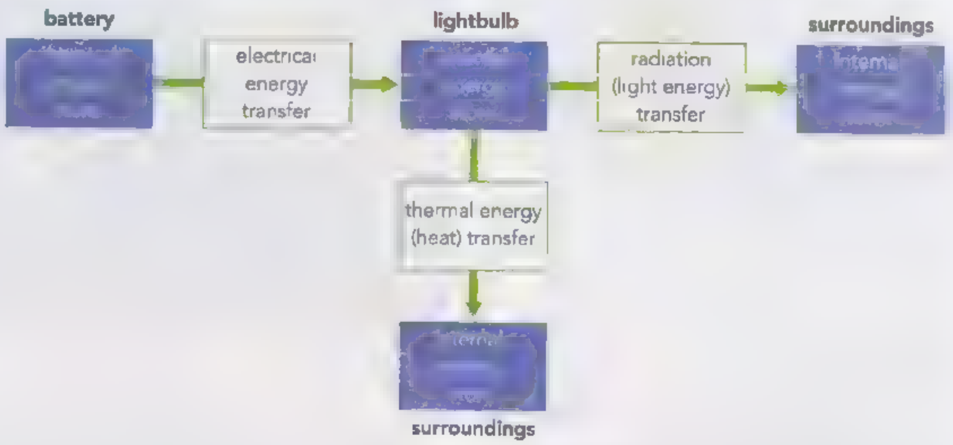


Figure 6.9: The energy stores and transfers associated with a battery-powered lamp. The stores are indicated by blue boxes and the transfers by the green boxes with arrows.

Heat or thermal energy moves along the thermocouple from the hot end to the cold end (down a temperature gradient). The temperature difference at the junction of the two metals produces a voltage.

The nuclear energy in the fuel changes store several times. It transfers from the nuclear store to the internal energy store of the fuel. It then transfers as thermal energy as it moves along the thermocouples. At the junction of the two metals, it transfers as electrical energy.

nuclear energy (store) → internal energy (store) → thermal energy (transfer) → electrical energy (transfer)

These energy changes can be represented in the energy flow diagram in Figure 6.11.

Shooting an arrow is an event, but a rocket launch is a process. The rocket in Figure 6.12 is lifting off from the ground as it carries a new spacecraft up into space. Its energy comes from its store of chemical energy (tanks of liquid hydrogen) and oxygen. When the hydrogen fuel burns in oxygen, its store of chemical energy is released.

The rocket is accelerating, so we can say that its kinetic energy is increasing. It is also rising upwards, so its gravitational potential energy is increasing. In Figure 6.12, you can see light coming from the burning fuel. You can also imagine that large amounts of thermal energy and sound energy are transferred into the atmosphere.

These energy changes could be represented as an energy flow diagram as before or as an equation:

chemical energy → k.e. + g.p.e. + thermal energy + light energy + sound energy

Figure 6.12: This rocket uses rocket motors to lift it up into space. Each rocket motor burns about one tonne of fuel and oxygen every minute to provide the energy needed to move the rocket upwards

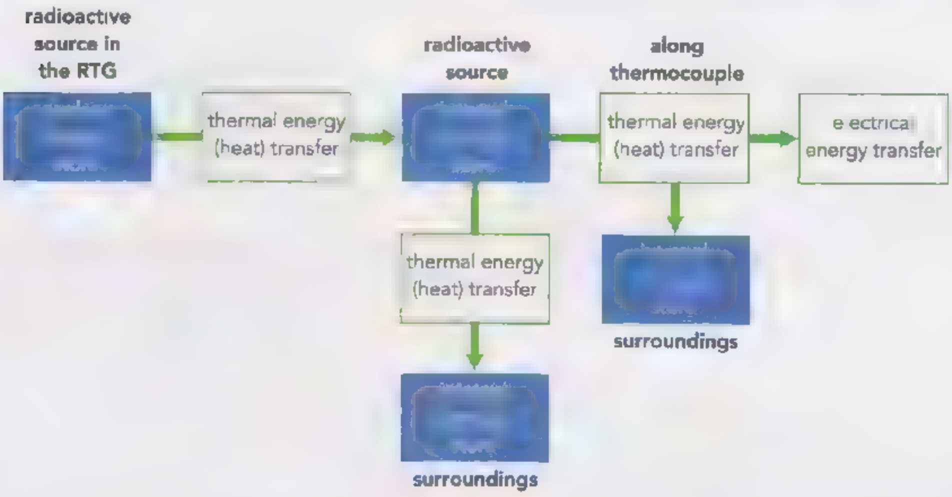


Figure 6.11: The energy flow diagram for the RTG. The blue boxes represent stores and the green boxes are the transfers

Question

7 What energy transfers are going on in the following? In each case, write an equation to represent the energy transfer

a Coal is burned to heat a room and to provide a supply of hot water.

b A student uses an electric lamp while she is doing her homework

c A hair dryer is connected to the mains electricity supply. It blows hot air at the user's wet hair. It whirrs as it does so

Energy changes

Examine some devices that transfer energy. Some ideas are shown in Figure 6.1 in the 'Getting Started' box.

- In pairs, examine each of the devices you are provided with For each of them, describe what energy transfers are going on in the device.
- With your partner, decide how to record and present the energy transfers you have described for each device
- Compare your answers with the answers of other members of the class and correct or add to your own answers.

6.3 Conservation of energy

When energy is transferred from one store to another, it is often the case that some of the energy ends up as unwanted energy The energy transfers in a light bulb were shown in Figure 6.9. The bulb transfers light (which we want) and heat (which is not wanted).

This is an example of a very important idea, the principle of conservation of energy:

> In any energy transfer, the total amount of energy before and after the transfer is constant.

This tells us something very important about energy: it cannot be created or destroyed. The total amount of energy is constant. If we measure or calculate the amount of energy before a transfer, and again afterwards, we will always get the same result If we find any difference, we must look for places where energy may be entering or escaping unnoticed.

principle of conservation of energy energy cannot be created or destroyed; it can only be stored or transferred

A car burns 3×10^5 J of fuel (chemical energy) per second. It has 1.3×10^5 J of kinetic energy and gains 0.7×10^5 J of gravitational potential energy as it goes up a slope. How much energy transfers away from the car through thermal energy transfer? Assume that acceleration due to gravity $g = 10$ m/s^2

Step 1: Write down what you know, and what you want to know

input energy.

chemical energy $= 3 \times 10^5$ J

output energy:

kinetic energy $= 1.3 \times 10^5$ J

gravitational potential energy $= 0.7 \times 10^5$ J

thermal energy transferred = ?

Step 2: Write down any equations or useful principles.

According to the principle of conservation of energy, the total input energy should equal the total output energy

Step 3: Apply the principle to this problem and substitute known values to solve the problem.

chemical energy = k.e. + g.p.e. + thermal energy

3×10^5 J $= 1.3 \times 10^5$ J $+ 0.7 \times 10^5$ J + thermal energy

$= 1.0 \times 10^5$ J transfers away from the car through thermal energy transfer

Answer

1.0×10^5 J transfers away from the car as thermal energy

Question

8 A light bulb is supplied with 60 J of energy each second.

a How many joules of energy are transferred from the bulb each second?

b 4 J of energy are transferred from the lamp each second as light. How many joules of energy are transferred each second by heating?

Sankey diagrams

An effective way to represent the principle of conservation of energy is by using a **Sankey diagram**. The rocket motor we saw earlier (Figure 6.12) does mechanical work to transfer chemical energy into k.e. and g.p.e. (energy stores that we do want), while heat, light and sound transfer energy to the internal energy store of the surroundings (an energy store that we do not want to increase). This is shown in Figure 6.13.

Figure 6.13 The energy changes going on as a rocket like that in Figure 6.12 accelerates upwards. Chemical energy in the fuel is released when it burns in oxygen and is transferred into three other energy stores.

[illegible]

Sankey diagram: a flow diagram that represents the principle of conservation of energy; the width of the arrows is proportional to energy

At the beginning of Chapter 1 you were introduced to the Ancient Egyptians and their pyramids. The Egyptians built their pyramids by dragging limestone blocks up ramps and Figure 6.14 shows the Sankey diagram for this. By doing mechanical work, they transferred energy from the chemical energy store in their bodies to the (useful) gravitational potential energy gained by the blocks. At the same time some of their store of chemical energy is transferred, by heating, to the (useless) internal energy of the surroundings. This heat came from their bodies and because of friction between the blocks and the ramp.

Figure 6.14: A Sankey diagram for blocks being dragged up a ramp

Energy efficiency

Most wasted energy is transferred away as heat. There are two main reasons for this.

When fuels are burned (perhaps to generate electricity, or to drive a car), heat is produced. Any kind of engine needs a difference in temperature to create movement. Thermal energy transfers from the hot part to the cold part of the engine and kinetic energy is produced. But no matter how well insulated the hot part is, it will transfer thermal energy to the surroundings. Or, the cold part has to be cooled to maintain (keep) the temperature difference. So, power stations produce warm cooling water and cars produce hot exhaust gases.

Friction is often a problem when things are moving. **Lubrication** can help to reduce friction and no doubt the Egyptians lubricated the ramps to make it easier for the blocks to be dragged up them. A streamlined car design can reduce air resistance. But it is impossible to eliminate (remove) friction entirely from machines with moving parts. Friction generates heat.

Another common wasted energy transfer is sound. Noisy machinery, loud car engines and so on, all transfer sound to the atmosphere. However, even loud noises contain very little energy, so there is little to be gained (in terms of energy) by reducing noise.

It is important to make good use of the energy resources available to us. This is because energy is expensive, supplies are often limited, and our use of energy can damage the environment. So we must use resources efficiently. Here is what we mean by **efficiency**:

> Efficiency is the fraction (or percentage) of energy supplied that is usefully transferred.

Be careful, the word, 'efficiency' is often used in everyday life, but often it is used to mean quickly, which is not the same as the scientific meaning.

lubrication: usually a liquid, it allows two surfaces to slide past each other more easily

efficiency: the fraction (or percentage) of energy supplied that is usefully transferred

Table 6.3 shows the typical efficiencies for some important devices. You can see that even the most modern gas-fired power station is only 50% efficient. Half of the energy it is supplied with is wasted.

Device	Typical efficiency
electric heater	100%
large electric motor	90%
washing machine motor	70%
gas-fired power station	50%
diesel engine	40%
car petrol engine	30%
steam locomotive	10%

Table 6.3: Energy efficiencies. Most devices are less than 100% efficient because they produce waste heat. An electric heater is 100% efficient because all of the electrical energy supplied is transferred to thermal energy. There is no problem with waste here.

Questions

9 a In what way is energy usually wasted?

b Name another way in which energy is often wasted.

10 Give three reasons why it is important not to waste energy.

Making better use of energy

Figure 6.15 shows a Sankey diagram that represents energy flows in the whole of the UK in a typical year. Most of the energy flowing in to the UK comes from fuels, particularly coal, oil and gas. Energy is wasted in two general ways: when it is changed into electricity and while it is being used (for example, in light bulbs).

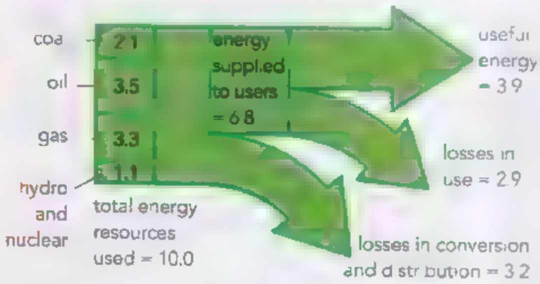


Figure 6.15: Energy flows in the UK in the year 2000. All numbers are $\times 10^{18}$ J. A large proportion of the energy supplied by fuels is wasted in energy transfer processes and during its final use. Some of this waste is inevitable, but better insulation and more efficient machines could reduce the waste and environmental damage, and save money.

Figure 6.16 shows one way to make more efficient use of electricity. We use light bulbs to provide us with light. The lower light bulb is a filament lamp, the other one is an energy-efficient lamp. The Sankey diagrams show the energy each light bulb transfers each second. The diagram shows that each of the two bulbs produces the same amount of light. However, because it wastes much less energy as heat, the energy-efficient lamp requires a much smaller input of energy and is more efficient.

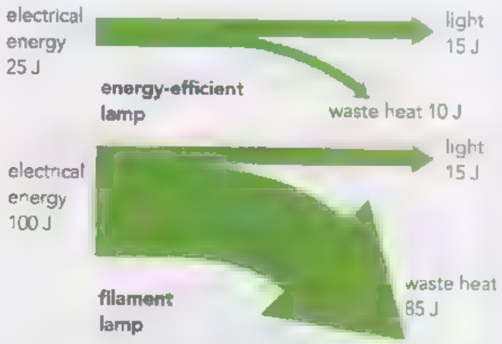


Figure 6.16: Each of these two light bulbs provides the same amount of light. The energy-efficient lamp wastes much less energy as heat.

Try not to mix stores and transfers on the same Sankey diagram. Figures 6.13 and 6.14 shows energy stores while Figure 6.16 shows transfers. Figure 6.16 shows the energy used by the light bulbs per second. Energy transferred per second is known as power and is something you will meet in Chapter 8. This highlights an important difference between stores and transfers. Transfers are a flow of energy.

Energy becoming dissipated

We have seen that energy changes are usually less than 100% efficient. Energy escapes and is wasted as heat. This means that objects and their surroundings are warmed (and gain some internal energy). It is very difficult to get that energy back. We say that energy tends to be **dissipated** (spread out) during an energy transfer.

Think about, for example, a battery in a flashlight. It is a convenient, compact store of energy. Once it has been used, some of its energy has been changed to light which is then absorbed by the surfaces it falls on, causing them to warm slightly (raising their internal energy). The rest of the energy is dissipated as thermal energy in the components of the electric circuit in the flashlight.

[illegible]

dissipated: energy that is spread out is not useful (wasted)

Calculating efficiency

You can see from Table 6.3 that efficiency is often given as a percentage. We can calculate the efficiency and percentage efficiency of an energy change as follows:

[illegible]

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

$$\text{percentage efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

$$\text{percentage efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

Efficiency is expressed as a number (no units) up to a value of 1. This number can be multiplied by 100 to get percentage efficiency. Percentage efficiency greater than 100% is impossible.

When the filament lamp from Figure 6.16 is supplied with 100 J of energy, it produces 15 J of useful light. Its efficiency is thus:

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

$$= \frac{15\,\text{J}}{100\,\text{J}} = [illegible]$$

$$\text{percentage efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

$$= \frac{[illegible]}{100\,\text{J}} \times 100\% = 15[illegible]$$

Similar equations can be used to calculate the efficiency and percentage efficiency in terms of power as follows:

$$\text{efficiency} = \frac{\text{useful power output}}{\text{total power input}}$$

$$\text{percentage efficiency} = \frac{\text{useful power output}}{\text{total power input}} \times 100\%$$

Questions

11 Describe the energy transfers taking place when charging a mobile phone, including the energy that is wasted.

12 Calculate the efficiency of the energy-efficient lamp from the data shown in Figure 6.16.

13 A tidal-power station is expected to produce 32 TJ of energy (1 TJ = 10^{12} J) when the tides provide it with 100 TJ of gravitational potential energy. What is the efficiency of the power station?

14 A tungsten-filament lamp is 4% efficient. How much electrical energy must be supplied to the lamp each second when it produces 6 J of light per second?

ACTIVITY 6.2

Energy changes during the pole vault

Energy is transferred between different energy stores during the pole vault. Snapshots (labelled 1–5) of an athlete at different stages of the pole vault are as shown in Figure 6.17. Between each snapshot, the energy is transferred between stores.

1 Copy and complete this table.

Snapshot	Main energy store	Additional energy stores	Wasted energy
1			
2			
3			
4			
5			

2 How is the energy transferred between each store?

3 Using Figure 6.9 as a guide, draw an energy flow diagram that shows the main energy stores and the energy transfers between them.

4 Decide whether you think the pole vault is an event or a process and justify your answer.

5 If your teacher gives you the time to do so, compare your answers with your neighbour and try to resolve any differences. Be prepared to discuss your thinking with the class.

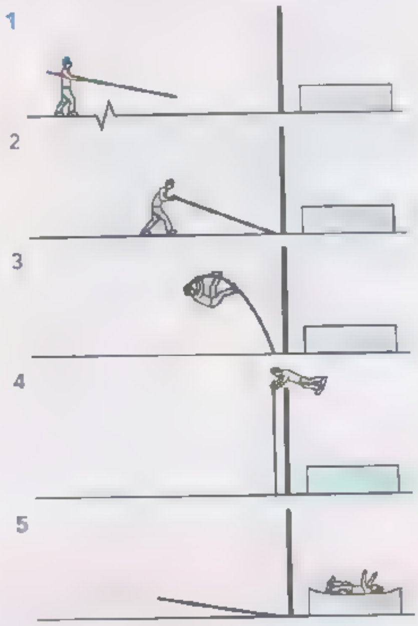


Figure 6.17: Pole vaulter.

SELF-ASSESSMENT

Think about Activity 6.2. Did you find this activity easy? If you found it difficult, you could think about energy transfers that you come across every day (for example, the transport you use to get to and from school) and ask a friend to check your answer.

6.4 Energy calculations

Energy is not simply an idea; it is also a quantity that we can calculate.

Gravitational potential energy (g.p.e.)

Mountaineering on the Moon should be easy (see Figure 6.18). The Moon's gravity is much weaker than

[illegible]

eightieth of the Earth's. This means that the weight of an astronaut on the Moon is a fraction of his or her weight on the Earth. In principle, it is possible to jump higher on the Moon than on the Earth.

[illegible]

height above the ground. The higher it is, the gre[illegible] g.p.e. If you lift an object upwards, you provide the force needed to increase its g.p.e. The heavier the object, the greater the force needed to lift it, and hence the greater its g.p.e.

ACTIVITY 6.?

Figure 6.18: Astronauts on the Moon. The gravitational field strength on the surface of the Moon is one-sixth of what it is on Earth. Experiments on the Moon have shown that a golf ball can be hit much further than on Earth. This is because it travels a much greater distance horizontally before gravity pulls it back to the ground.

This suggests that an object's gravitational potential energy (g.p.e.) depends on two factors:

- the object's weight, mg – the greater its weight, the greater its g.p.e.
- the object's height, h, above ground level – the greater its height, the greater its g.p.e.

This is illustrated in Figure 6.19. From the numbers in the diagram, you can see that a change in g.p.e. is simply calculated by multiplying weight by height. (Here, we are assuming that an object's g.p.e. is zero when it is at ground level.) We can write this as an equation for g.p.e.

KEY EQUATION

change in g.p.e. = weight × change in height

$$\Delta E_p = mg\Delta h$$

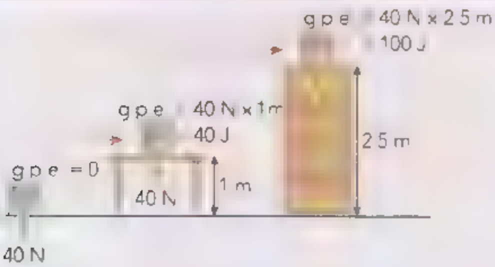


Figure 6.19: The gravitational potential energy of an object increases as it is lifted higher. The greater its weight, the greater its g.p.e.

WORKED EXAMPLE

An athlete of mass 50 kg runs up a hill. The foot of the hill is 400 metres above sea-level. The summit is 1200 metres above sea-level. By how much does the athlete's g.p.e. increase? Assume that acceleration due to gravity g = 10 m/s².

Step 1: Assume that g.p.e. is zero at the foot of the hill. Calculate the increase in height.

Δh = 1200 m − 400 m = 800 m

Step 2: Write down the equation for g.p.e., substitute values and solve.

ΔE_p = weight × change in height

$= mg\Delta h$

$= 50\text{ kg} \times 10\text{ m/s}^2 \times 800\text{ m}$

$= 400\,000\text{ J}$

$= 400\text{ kJ}$

Answer

The athlete's g.p.e. increases by 400 kJ.

A note on height

We have to be careful when measuring or calculating the change in an object's height.

First, we have to consider the vertical height through which it moves. A train may travel 1 km up a long and gentle slope, but its vertical height may only increase by 10 metres. A satellite may travel around the Earth in a circular orbit. It stays at a constant distance from the centre of the Earth and so its height does not change. Its g.p.e. is constant.

Second, it is the change in height of the object's centre of gravity that we must consider. This is illustrated by the pole-vaulter shown in Figure 6.20. As he jumps, he must try to increase his g.p.e. enough to get over the bar. In fact, by curving his body, he passes over the bar but his centre of gravity may pass under it.

Figure 6.20: This pole-vaulter adopts a curved posture to get over the bar. He cannot increase his g.p.e. enough to get his whole body above the level of the bar. His centre of gravity may even pass under the bar, so that at no time is his body entirely above the bar.

Moon flight high jump

	High jump record / m	Athlete	Height of athlete / m	Year
men	2.45	Javier Sotomayor (Cuba)	1.95	1993
women	2.09	Stefka Kostadinova (Bulgaria)	1.80	1987

Table 6.4

Table 6.4 lists the current world records for the high jump.

Predict what the high jump record would be on the lunar surface.

Now follow these steps to see if your prediction was correct.

1. Let us assume that the Moon has the same atmosphere as Earth, and that the athletes can reach the same run-up speed. Imagine that the gravitational field strength on the Moon is reduced to one sixth of the value it has on the Earth's surface (10 N/kg) only after the jumpers have lifted off the ground. Predict what you think the high jump records would be on the Moon. Write down your working and your answers.
2. Now assume that the centre of gravity of a person is located half-way up their body. Through what height have these athletes moved their centre of gravity in order to achieve their world records?
3. The athletes are doing physical work to raise their centres of mass over the bar. Now that you know the jumpers are raising their centres of gravity, work out a revised prediction for the records, but take care, as there is still a potential trap for the unwary.
4. Most high jumpers now use a technique that allows their centre of gravity to pass below the bar, by as much as 20 cm. Explain or sketch how this is possible.
5. Can you explain why the height gained by the athlete when they jump is not the distance between the bar and the ground?
6. Use physics to explain why successful high jumpers tend to be tall and slim.
7. Make a case for medals being awarded to athletes who can raise their centres of gravity through the biggest height.

Kinetic energy

It takes energy to make things move. You transfer energy to a ball when you throw it or hit it. A car uses energy from its fuel to get it moving. Elastic energy stored in a stretched piece of rubber is needed to fire a pellet from a catapult. So a moving object is a store of energy. This energy is known as kinetic energy (k.e.).

We often make use of an object's kinetic energy. To do this, we must slow it down. For example, moving air turns a wind turbine. This slows down the air, reducing its k.e. The energy extracted can be used to turn a generator to produce electricity.

This suggests that the kinetic energy of an object depends on two factors:

- the object's mass m – the greater the mass, the greater its kinetic energy
- the object's speed v – the greater the speed, the greater its kinetic energy

These are combined in an equation for kinetic energy.

kinetic energy = $\frac{1}{2}$ × mass × speed²

$$E_k = \frac{1}{2}mv^2$$

Worked Example 6.3 shows how to use the equation to calculate the kinetic energy of a moving object. Note also that kinetic energy is a scalar quantity, despite the fact that it involves v. It is best to think of v here as speed rather than velocity.

WORKED EXAMPLE 6.3

A van of mass 2000 kg is travelling at 10 m/s.

a Calculate its kinetic energy.

b Its speed increases to 20 m/s. By how much does its kinetic energy increase?

Step 1: Calculate the van's kinetic energy at 10 m/s.

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 2000\,\text{kg} \times (10\,\text{m/s})^2$$
$$= 100\,000\,\text{J}$$
$$= 100\,\text{kJ}$$

Step 2: Calculate the van's kinetic energy at 20 m/s.

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 2000\,\text{kg} \times (20\,\text{m/s})^2$$
$$= 400\,000\,\text{J}$$
$$= 400\,\text{kJ}$$

Step 3: Calculate the change in the van's kinetic energy.

change in kinetic energy = 400 kJ − 100 kJ
= 300 kJ

Answer

a The van's k.e. when travelling at 10 m/s is 100 kJ.

b The van's k.e. increases by 300 kJ when it speeds up from 10 m/s to 20 m/s.

When the van starts moving from rest and speeds up to 10 m/s, its kinetic energy increases from 0 to 100 kJ. When its speed increases by the same amount again, from 10 m/s to 20 m/s, its kinetic energy increases by 300 kJ, three times as much. It takes a lot more energy to increase your speed when you are already moving quickly. That is why a car's fuel consumption starts to increase rapidly when the driver tries to accelerate in the fast lane of a motorway.

It is worth looking at Worked Example 6.3 in detail, since it illustrates several important points.

When calculating kinetic energy using $E_k = \frac{1}{2}mv^2$, take care! Only the speed is squared. Using a calculator, start by squaring the speed. Then multiply by the mass, and finally divide by two.

When the van's speed doubles from 10 m/s to 20 m/s, its kinetic energy increases from 100 kJ to 400 kJ. In other words, when its speed increases by a factor of two, its kinetic energy increases by a factor of four. This is because kinetic energy depends on speed squared. If the speed trebled (increased by a factor of three), the kinetic energy would increase by a factor of nine (see Figure 6.21).

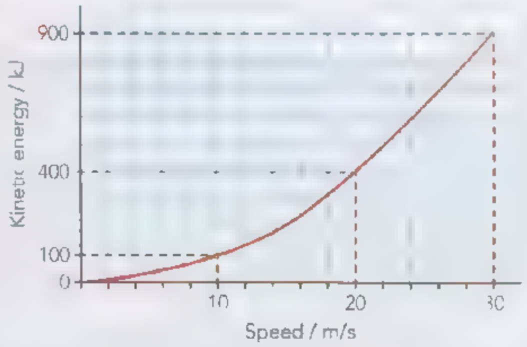


Figure 6.21: The faster the van travels, the greater its kinetic energy. The graph shows that kinetic energy increases more and more rapidly as the van's speed increases.

Questions

15 In the following examples, is the object's g.p.e. increasing, decreasing or remaining constant?

a A balloon rises in the air.

b A bird flies at a constant height on its migration route.

c A raindrop falls from the sky.

16 It is claimed that Superman can jump 200 metres vertically upwards. If he has a mass of 100 kg, by how much does his g.p.e. increase?

17 A raindrop weighs 1×10^{-3} N. Its g.p.e. decreases by 0.8 J when it falls from a cloud. How high was the cloud?

18 What does v represent in the equation $E_k = \frac{1}{2}mv^2$?

19 How much kinetic energy is stored by a bullet with a mass of 10.5 g travelling at 553 m/s?

20 Usain Bolt has a mass of 86 kg. When he runs at 12 m/s, what is his kinetic energy?

21 Which has more kinetic energy, a 2.0 g bee flying at 1.0 m/s, or a 1.0 g wasp flying at 2.0 m/s?

How easy did you find this topic?

How will you learn the different energy stores and transfers and remember the difference between them?

If you do not know the difference between an event and a process, how are you going to find out?

Choose one of the options below and either produce a short report (less than 500 words) along with relevant illustrations or produce a short presentation (two or three minutes), with suitable visual aids.

Option 1: Inventions for remote places

Research an invention that provides useful energy in a location without an obvious or reliable energy supply. If you cannot track down another invention, focus on one of the following examples.

- You should already have met the radioisotope thermoelectric generator (RTG) earlier in the book.
- Trevor Baylis invented the wind-up radio, which worked without batteries or access to an electrical power source.

Option 2: Efficiency

It is important to increase efficiency to reduce waste, reduce environmental damage, and save money. Investigate efforts to improve the efficiency of one device (for example, a light bulb, or a car) or create better insulation for homes.

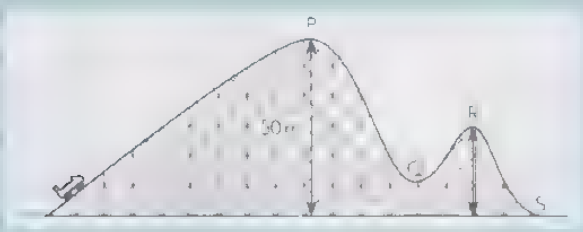
Transfers between different stores of energy can occur because of an event or process.
A collision is an event that will change the kinetic energy of a body
Heating a body will increase its internal energy.
Changing the shape of a body will change its elastic (strain) energy
Lifting a body will increase its g.p.e.

CONTINUED

Burning a substance will reduce its chemical energy
Energy can be transferred between energy stores, which can be illustrated using an energy flow diagram
Mechanical work can transfer g.p.e. to an object, by lifting it
Electric currents transfer energy electrically
Thermal energy can transfer internal energy from a hot object to a cold object
It is important to increase efficiency to reduce waste, reduce environmental damage, and save money.
When a process is not 100% efficient, the wasted energy spread outs and is not useful (usually thermal energy)
Energy is conserved. It cannot be created or destroyed; it can only transfer from one store to another.
A Sankey diagram illustrates the principle of conservation of energy.
Efficiency is the fraction of the total energy that is useful.
change in gravitational potential energy = weight × change in height or change in gravitational potential energy = mass × gravitational field strength × change in height or $\Delta E_p = mg\Delta h$.
kinetic energy is $E_k = \frac{1}{2}mv^2$.
When working out kinetic energy, only the speed is squared

EXAM-STYLE QUESTIONS

1 This diagram shows an amusement park roller coaster ride (not drawn to scale).



a On what part of the ride is the car moving slowest? [1]

b On what part of the ride is the car moving fastest? [1]

c The car becomes stuck at point P, which is 50 metres above the ground. To the relief of the passengers, the car eventually moves again and passes point R at 20 m/s. Approximately how high is point R? The car and its passengers have a combined mass of 700 kg (though the question can be answered without this information). [1]

A 35 m/s
B 30 m/s
C 25 m/s
D 20 m/s

[Total: 3]

CONTINUED

2 Copy and complete the table. For each description, write down the name of the associated energy and state whether it is a store or transfer. [2]

Description	Name of energy	Store or transfer
energy of a moving object		
energy in a hot object		
energy in a fuel		
energy that we can see		
energy in a squashed spring		
energy carried by an electric current		
energy in the nucleus of an atom		
energy escaping from a hot object		

3 Which of the following statements is closest to the meaning of the principle of conservation of energy? [1]

A Energy can only be stored or transferred
B Energy is created by energy stores
C Energy can be destroyed by transfers
D Energy can only be transferred

4 This diagram represents an energy transfer.

Copy and complete the following two word equations for this energy change:

a wasted energy = ______ [1]

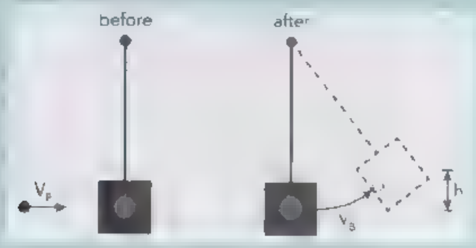
b efficiency = _____ [1]

[Total: 2]

express in clear terms

CONTINUED

5 Scientists use a ballistic pendulum to work out the speed of a projectile that hits it. The block has a mass of 4.7 kg and moves with an initial speed of 1.24 m/s when it is hit.



a State the equation linking kinetic energy, mass and velocity. **[1]**

b Calculate the kinetic energy of the block. **[2]**

c As the block swings, it gains g.p.e. What is the maximum g.p.e. that can be gained by the block. **[1]**

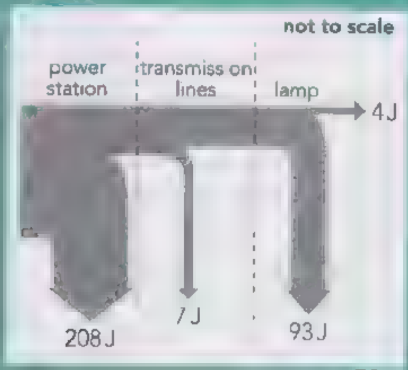
d Calculate the maximum height the block gains. **[2]**

e It might not be easy to measure the height increase. Suggest another variable a researcher could measure more easily and then use to get the height. **[1]**

f Researchers find the kinetic energy of the projectile is much higher than the kinetic energy of the block. What happened to the kinetic energy that was not transferred from the projectile to the block? **[1]**

[Total: 8]

6 This is the Sankey diagram for a 100 W light bulb.



a Calculate the input energy to the power station.

b Calculate the efficiency of the power station.

c Calculate the efficiency of the light bulb.

d [illegible]

calculate: work out from given facts, figures or information

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible] work	[illegible] there	[illegible] to move on
Recall the different names of energy stores (k.e., g.p.e., chemical, elastic, nuclear, internal, electrostatic, magnetic) and transfers (electrical, thermal, radiation, mechanical).	6.1, 6.2			
Recognise how energy is transferred during events and processes.	6.2			
Interpret energy flow diagrams.	6.2			
Understand the meaning of efficiency.	6.3			
Understand and apply the principle of conservation of energy.	6.3			
Calculate using the equations for percentage efficiency.	6.3			
Explain that, in any event or process, the energy tends to become more spread out among the objects and surroundings.	6.3			
Recall and use the equation for kinetic energy $E_k = \frac{1}{2}mv^2$.	6.4			
Recall and use the equation for a change in g.p.e., $E_p = mg\Delta h$	6.4			

> Chapter 7

Energy resources

- describe how electricity or other useful stores of energy may be obtained from different energy resources
- give advantages and disadvantages of each energy resource in terms of renewability, cost, reliability, availability, scale and environmental impact

> [illegible] nuclear and tidal

> [illegible]

[illegible]

List all the energy resources that you know. Examples of energy resources include wood for heating and cooking.

Which of these energy resources are renewable?

Can any of these resources be traced back to sunlight?

IS THORIUM THE PERFECT FUEL?

Kirk Sorensen worked for NASA to come up with a reliable source of energy for a Moon base. None of the energy resources that are used on Earth were suitable. But then he found a book about liquid fluoride thorium reactors (or 'lifters'), an environmentally friendly and safe version of nuclear power. They were being developed by the USA so that aircraft carrying nuclear bombs would only have to land to change crews and take on supplies. But the experiment was abandoned in 1956 because missiles could more easily send nuclear bombs over great distances.

Nuclear power stations need water but a lifter would not, making it suitable for the Moon.

But Sorenson thought, 'why not have them here on Earth?' There are huge reserves of thorium fuel available, they produce tiny amounts of radioactive waste, an accidental meltdown would be impossible, and it would be extremely difficult to make a nuclear bomb using a lifter.

Discussion questions

1. Explain why energy resources used on Earth would not be suitable for the Moon.
2. Would you be in favour of nuclear power based on a lifter? Explain your answer.

Figure 7.1: Pellets of thorium.

7.1 The energy we use

Here on Earth, we rely on the Sun for most of the energy we use. The Sun is a fairly average star, 150 million kilometres away The heat and light we receive from it take about eight minutes to travel through empty space to get here. Plants absorb this energy in the process of photosynthesis, and animals are kept warm by it.

The Earth is at a convenient distance from the Sun for living organisms. The Sun's rays are strong enough, but not too strong. The Earth's average temperature is about 15 °C, which is suitable for life. If the Earth were closer to the Sun, it might be intolerably hot like Venus, where the average surface temperature is over 400 °C Further out, things are colder. Saturn is roughly ten times as far from the Sun, so the Sun in the sky looks one-tenth of the diameter that we see it, and its radiation has only one-hundredth of the intensity. Saturn's surface temperature is about −180 °C

Most of the energy we use comes from the Sun, but only a small amount is used directly from the Sun. On a cold but sunny morning, you might sit in the sunshine to warm your body. Your house might be designed to collect warmth from the Sun's rays, perhaps by having larger windows on the sunny side. However, most of the energy we use comes only indirectly from the Sun. It must be transferred in a more useful form, such as electricity.

Figure 7.2 shows the different fuels that contribute to the world's energy supplies. This chart reflects patterns of energy consumption in 2018 Many people today live in industrialised countries and consume large amounts of energy, particularly from fossil fuels (coal, oil and gas). People living in less-developed countries consume far less energy mostly they use biomass fuels, particularly wood A thousand years ago, the chart would have looked very different. Fossil fuel consumption was much less important then. Most people relied on burning wood to supply their energy requirements. We will now look at these groups of fuels in turn, in addition to other energy resources. Energy resources are not the same as the stores and transfers of energy you studied in Chapter 6

However, we first need to categorise (group together) energy resources to make it easier to compare them. So, we will look at how most of them can be used to generate electricity and whether or not they are renewable.

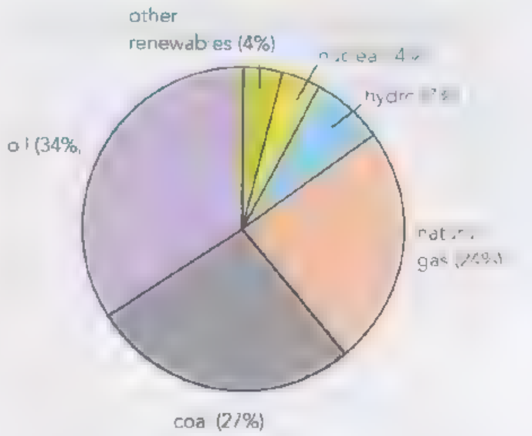


Figure 7.2: World energy use, by fuel This chart shows people's energy consumption of different fuels across the world in 2018 Around 85% of all energy comes from fossil fuels

Renewables and non-renewables

Figure 7.2 shows that most of the energy supplies we use are fossil fuels – coal, oil and gas. Oil and natural gas are expected to run out this century but reserves of coal should last another 200 years. They are described as **non-renewables**. Once used, they are gone forever

Other sources of energy, such as wind, solar and biofuel, are described as **renewables**. This is because, when we use them, they will soon be replaced. The wind will blow again, the Sun will shine again. After harvesting a biofuel crop, we can grow another crop.

Ideally, our energy supply should be based on renewables. Then we would not have to worry about supplies running out. As we will see, non-renewable resources also cause significant environmental problems. Burning fossil fuels causes global warming while nuclear power produces dangerous radioactive waste.

non-renewables: an energy resource that is gone forever once it has been used

renewables: an energy resource that will be replenished (replaced) naturally when used

Create a presentation on an energy resource

Research a particular energy resource and present your work to the class. Work in groups of two or three

Your two to three minute presentation should answer these questions

- What is the origin of the energy resource?
- Is the energy resource renewable or non-renewable?
- If the resource is used to generate electricity, what energy transfers happen and how it is done?
- What are the advantages and disadvantages of using this energy resource compared with others?

The presentation should make use of audio-visual technology (such as presentation software), or you could produce a documentary.

The presentation will be graded by the rest of the class on its scientific content and the quality of its delivery (in other words, how well it is presented).

You should also prepare a handout consisting of one side of A4 that summarises the points made in your presentation

Energy direct from the Sun

In hot, sunny countries, **solar panels** are used to collect energy transferred by light from the Sun. The Sun's rays fall on a large solar panel, on the roof of a house, for example. This absorbs the energy of the rays, and water inside the panel heats up. This provides hot water for washing. It can also be pumped round the house, through radiators, to provide a cheap form of central heating.

We can also generate electricity directly from sunlight (Figure 7.3). The Sun's rays shine on a large array of **solar cells** (also known as a **photocells** or **photovoltaic cells**). The solar cells absorb the energy of the rays, and electricity is produced.

While solar power (from solar panels and photocells) is renewable and does not contribute to global warming, it is unreliable because the intensity of sunlight varies (and drops to zero at night) and a large area of solar panels is required to capture the energy

However, as this technology becomes cheaper, it is finding more and more uses. It is useful in remote locations. For example, for running a refrigerator that stores medicines in central Africa, or for powering roadside emergency phones in desert regions such as the Australian outback. Solar cells have also been used extensively for powering spacecraft. Ideally, a solar cell is connected to a rechargeable battery, which stores the energy collected, so that it can be available during the hours of darkness.

solar panel: used to collect energy that is transferred by light from the Sun

solar cell/photocell/photovoltaic cell: an electrical device that transfers the energy of sunlight directly to electricity, by producing a voltage when light falls on it

Figure 7.3: An array of solar cells inside the Vansad National Park, India

Wind power

Wind and waves are also caused by the effects of the Sun. The Sun heats some parts of the atmosphere more than others. Heated air expands and starts to move around – this is a convection current (see Chapter 11). This is the origin of winds. There are many technologies for extracting energy from the wind. Windmills have been used for a long time for grinding and pumping, and modern wind turbines can generate electricity (see Figure 7.4)

Wind is renewable and does not contribute to global warming. However, it is unreliable because the speed of the wind can vary and on calm days no power is produced. Wind turbines need a minimum wind speed of about 5 m/s and are switched off when wind speeds exceed 25 m/s to prevent them being damaged.

Wind is a dilute energy resource. It would take a 'wind farm' of several hundred wind turbines (spread over several square kilometres) to produce the same energy as a typical fossil fuel power station. Wind turbines are also noisy and many people think they spoil the appearance of places where they are located

Figure 7.4: These giant turbines are part of a wind farm at Xinjiang in China. They produce as much electricity as a medium-sized coal-fired power station

Wave power

Most of the energy of winds is transferred to the sea as waves are formed by friction between wind and water. Like wind, wave power is renewable and does not contribute to global warming. However, it is unreliable because the height of waves can vary and, when there are no waves, no power is produced It is also difficult to convert the up-and-down motion of waves into the spinning motion required for a turbine in the wave energy converters, which float on the water. The cost is high because these machines corrode in the saltwater and can be damaged in storms.

Questions

1 Explain why wind power can be traced back to sunlight

2 What is the difference between a solar panel and a solar cell?

3 Describe the advantages and disadvantages of solar power.

Hydroelectric power

One of the smallest contributions to the chart in Figure 7.2 is hydroelectric power. For centuries, people have used the kinetic energy of moving water to turn water wheels, which then drive machinery. For example, they are used to grind corn and other crops, pump water and weave textiles. Today we have hydroelectric power stations (see Figure 7.5) Water stored behind a dam is released to turn turbines, which make generators spin. This is a very safe, clean and reliable way of producing electricity, but it is not without its problems. A new reservoir floods land that might otherwise have been used for hunting or farming. People may be made homeless, and wildlife habitats destroyed

Hydroelectric power stations have a very short start up time (the time between switching on a power station and energy being delivered) This makes them very useful for storing energy until there is a sudden surge (increase) in demand. The demand for electricity varies during the day: it is highest during the daytime (when most people are awake) and lowest during the night. Power stations that use fossil fuels and nuclear fuels take a long time to start up and stop so, once started, they are allowed to continue running. It would take too long to stop them when demand is low and then start them again for the next rise in demand. This means that sometimes (usually at night) too much electricity is supplied and battery technology is not currently good enough to store large amounts of energy. In some hydroelectric power stations (called pumped storage systems), the turbines can be reversed so that water can be pumped back up a mountain to the reservoir so that energy can be stored as gravitational potential energy. This water can be allowed to fall back down the mountain to produce electricity when demand rises.

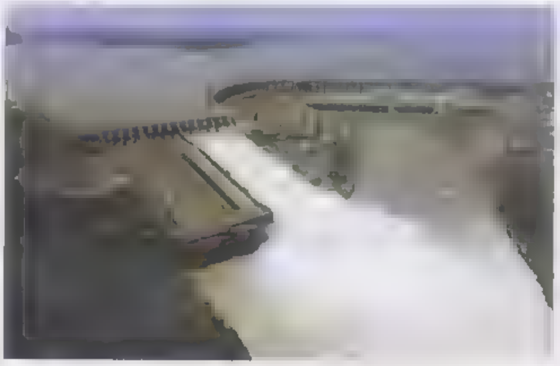


Figure 7.5: The giant Itaipú dam on the Paraná River in South America generates electricity for Brazil and Paraguay

Biomass fuels

For many people in the world, wood is the most important fuel. It warms their homes and provides the heat necessary for cooking their food. Wood is made by trees and shrubs. It stores energy that the plant has captured from sunlight in the process of photosynthesis. When we burn wood, we are releasing energy that came from the Sun in the recent past, perhaps ten or a hundred years ago.

Wood is just one example of a **biofuel**. Others include animal dung (Figure 7.6) and biogas, generated by rotting vegetable matter.

Figure 7.6: A Maasai blowing into elephant dung to make fire in a village in West Kilimanjaro, Tanzania

Biomass fuels account for roughly 10% of global energy consumption but, because no-one keeps track of all the wood consumed as fuel, it is a rough estimate. This means that it is rarely included in global figures and does not appear in Figure 7.2. About two-thirds of biomass fuel is used in developing countries for cooking and heating. The 25% of people in the developed (industrial) nations consume about six times as much energy as the other 75% of people living in the developing world.

Biomass has the advantage that it is renewable and does not contribute to global warming. It is reliable because it can be burned when needed. However, burning biofuels, particularly indoors, can lead to respiratory and other health problems.

Fossil fuels

Oil, coal and gas are all examples of **fossil fuels**. These are usually hydrocarbons (compounds of hydrogen and carbon). When they are burned, they combine with oxygen from the air. In this process, the carbon becomes carbon dioxide. The hydrogen becomes dihydrogen monoxide, which we usually call water. Energy is released.

We can write this as an equation:

hydrocarbon + oxygen → carbon dioxide + water + energy

Hence, we can think of a fossil fuel as a store of chemical energy. Where has this energy come from?

Fossil fuels (Figure 7.7) are the remains of organisms (plants and animals) that lived in the past. Many of the Earth's coal reserves, for example, formed from trees that lived in the Carboniferous era, between 286 and 360 million years ago. (Carboniferous means coal-producing.) These trees captured energy from the Sun by photosynthesis. They grew and eventually they died. Their trunks fell into swampy ground, but they did not rot completely, because there was insufficient oxygen.

KEY WORDS

biofuel: material, recently living, used as a fuel

fossil fuels: material, formed from long dead material, used as a fuel

Figure 7.7: Coal is a fossil fuel. A fossil is any living material that has been preserved for a long time. Usually, its chemical composition changes during the process. Coal sometimes shows evidence of the plant material from which it formed. Sometimes you can see fossilised creatures that lived in the swamps of the Carboniferous era. These creatures died along with the trees that eventually became coal.

As material built up on top of these ancient trees, the pressure on them increased. Eventually, millions of years of compression turned them into underground reserves of coal (Figure 7.7). Today, when we burn coal, the light that we see and the warmth that we feel have their origins in the energy from the Sun trapped by trees hundreds of millions of years ago.

Oil and gas are usually found together. They are formed in a similar way to coal, but from the remains of tiny shrimp-like creatures called microplankton that lived in the oceans. The oilfields of the Arabian Gulf, North Africa and the Gulf of Mexico, which contain half of the world's known oil reserves, all formed in the Cretaceous era, 75 to 120 million years ago.

Burning fossil fuels releases carbon dioxide into the atmosphere. This enhances (increases) the greenhouse effect and is the cause of recent global warming. Coal produces more carbon dioxide than oil and natural gas. Burning coal and oil usually also produces sulfur dioxide, which leads to acid rain and damage to ecosystems and buildings.

Questions

4 What form of energy is stored in fossil fuels and biofuels?
5 What is the difference between biofuels and fossil fuels?
6 Describe how fossil fuels are formed.

Nuclear fuels

Nuclear power was developed in the second half of the 20th century. It is a very demanding technology, which requires very strict controls, because of the serious damage that can be caused by an accident.

The fuel for a nuclear power station (Figure 7.8) is usually uranium, sometimes plutonium. These are radioactive materials. Inside a nuclear reactor, the radioactive decay of these materials is speeded up so that the energy they store is released much more quickly. This is the process of **nuclear fission**.

Uranium is a nuclear fuel. It is a very concentrated store of energy in the form of nuclear energy. A typical nuclear power station will receive about one truckload of new fuel each week. Coal is a less concentrated energy store. A similar coal-fired power station is likely to need a whole trainload of coal every hour. A wind farm capable of generating electricity at the same rate would cover a large area of ground – perhaps 20 square kilometres.

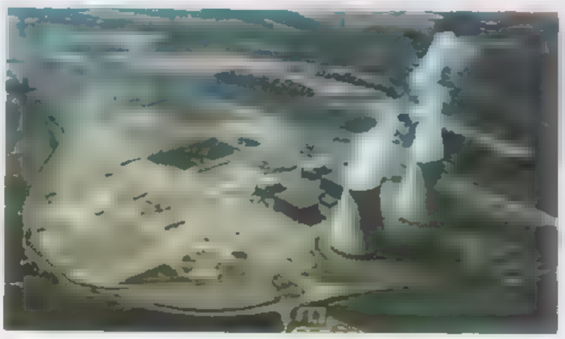


Figure 7.8: Belleville nuclear power station in France

nuclear fission: the process by which energy is released from nuclear fuels by the splitting of a large heavy nucleus into two or more smaller nuclei

In some countries that have few other resources for generating electricity, nuclear power provides a lot of energy. In France, for example, nuclear power stations generate three-quarters of the country's electricity. Excess production is exported to neighbouring countries, including Spain, Switzerland and the UK.

Nuclear fuel is a relatively cheap, concentrated energy resource. However, nuclear power has proved to be expensive because of the initial cost of building the power stations, and the costs of disposing of the radioactive spent fuel and decommissioning the stations at the end of their working lives. Also, accidents like those at Chernobyl in 1986 and Fukushima in 2011 can cause radioactive material to be spread over a wide area.

Geothermal energy

The interior of the Earth is hot. This would be a useful source of energy, if we could get at it. People do make use of this **geothermal energy** where hot rocks are found at a shallow depth below the Earth's surface. These rocks are hot because of the presence of radioactive substances inside the Earth. To make use of this energy, water is pumped down into the rocks, where it boils. High-pressure steam returns to the surface, where it can be used to generate electricity.

geothermal energy: energy stored in hot rocks underground

Suitable hot underground rocks are usually found in places where there are active volcanoes. Iceland, for example, has several geothermal power stations. These also supply hot water to heat nearby homes and buildings. While energy from geothermal resources has no obvious disadvantages, there are few places on Earth where it is available.

Tidal energy

A tidal power station is similar to a hydroelectric power station: electrical power is generated by moving water. A barrage (dam) is built across a river estuary (where a river meets the sea) creating a reservoir. As the tide goes in and out, water passes through turbines in the dam

Tidal power has the advantage of being renewable. Also, tides are predictable making it a fairly reliable energy resource. However, by flooding estuaries, a tidal power station can destroy wetlands, an important habitat for wildlife, particularly migrating birds that use it to feed and rest before the next leg of their journey. The barrage can also block shipping routes.

Questions

7 List the advantages and disadvantages of nuclear power

8 What energy is available from moving water?

9 In what way is a hydroelectric power station like a cell (or battery) and how can it be adapted to act like a rechargeable cell?

Using energy resources to generate electricity

Many of the energy resources in this chapter produce electricity so that it can be transferred to where it is needed. The thermal energy produced when fossil fuels are burned (Figure 7.9) or when nuclear fission takes place is used to heat water in a **boiler** to form steam. The steam turns the blades of a **turbine**, transferring thermal energy into kinetic energy. The turbine is linked by an axle to a **generator** where a voltage is induced in conducting wires when they move in a magnetic field. You will learn more about generators in Chapter 21

The details of how thermal energy is produced in power stations that use fuel will vary, but they will all have a boiler, turbine and generator. Those energy resources that do not use a fuel will not need a boiler, but they will still use a turbine linked to a generator to produce electricity Moving air (wind) and moving water (hydroelectricity, wave and tidal) can turn a turbine directly.

boiler: device where thermal energy is transferred to water to turn it into steam

turbine: a device that is made to turn by moving air, steam or water; often used to generate electricity

generator: a device which generates electricity using electromagnetic induction

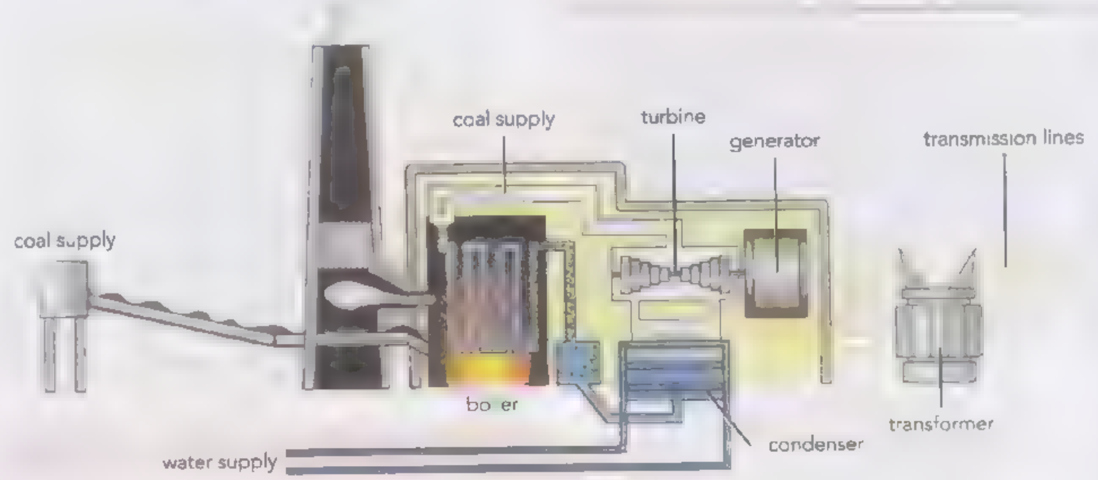


Figure 7.9: A schematic of coal-fired power station. The details of how thermal energy is produced in power stations that use fuel will vary but they will all have a boiler, turbine and generator

Comparing energy resources

We use fossil fuels a lot because they represent concentrated sources of energy A modern gas-fired power station might occupy the space of a football ground and supply a town of 100 000 people. To replace it with a wind farm might require 50 or more wind turbines spread over an area of several square kilometres. The wind is a much more dilute source of energy.

This illustrates some of the ideas that we use when comparing different energy resources. Each has its advantages and disadvantages. We need to think about the following factors.

Renewability

As we have seen, there are limited reserves of fossil fuels. The same applies to uranium nuclear fuel. However, there are plentiful reserves of alternative nuclear fuels like thorium. All other energy resources are renewable, including all those that can be traced back to radiation from the Sun. The most important advantage of renewable resources is that, once installed, they do not contribute to global warming.

Cost

We should separate initial costs from running costs. A solar cell is expensive to buy but there are no costs for fuels – sunlight is free! While nuclear fuel is cheap, the costs of decommissioning nuclear power plants are high.

Availability

France uses nuclear power to produce about 75% of its electricity because it has few alternative energy resources. Norway has plenty of rainfall and mountains so generates about 95% of its electricity from hydroelectric power. Iceland uses geothermal energy, which is quite localised.

Reliability

Is the energy supply constantly available? The wind is variable, so wind power is unreliable. Wars and trade disputes can interrupt fuel supplies.

Scale

A fossil fuel power station can be compact and still supply a large population. It would take several square metres of solar cells to supply a small household. Alternatively, people sometimes talk about how concentrated or dilute an energy resource is. When talking about fuels, they are comparing how much energy is stored in a certain mass of the fuel. Particularly when comparing wind turbines with other energy resources, people will talk about the land area required to generate the same amount of energy.

Environmental impact

The use of fossil fuels leads to climate change.
A hydroelectric dam may flood useful farmland.
Every energy source has some effect on the environment

Questions

10 Which of the following energy resources is renewable?

A oil
B nuclear
C biofuels
D coal

11 Which of the following energy resources is not renewable?

A hydroelectric power
B wind
C tidal
D nuclear

Sanghera Island

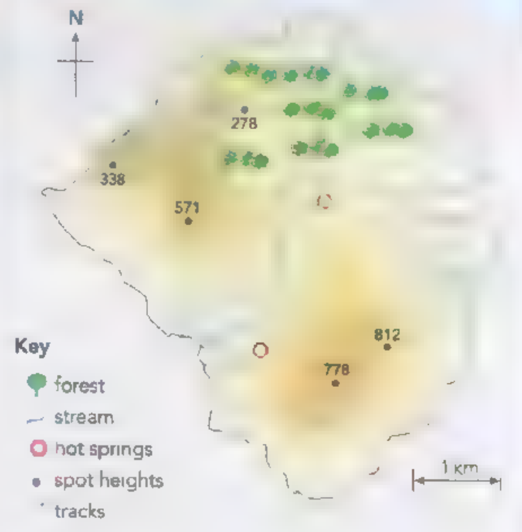


Figure 7.10: Map of Sanghera island

Part 1

Sanghera Island (Figure 7.10) is a remote fictitious island. It has no fossil fuels. It is hot with jungle vegetation, though it can sometimes be cold at night. High rainfall and mountainous terrain leads to fast-flowing streams. You are one of 25 members of a scientific expedition planning to study the island for three years. At the same time

CONTINUED

as minimising your impact (ecological footprint) on the island, you are the expert given the job of providing all the energy the team will need.

Answer the following questions to develop a plan that you will present to the team.

1 Describe two ways of providing hot water and heat for the buildings (living accommodation and laboratory).

2 Describe two possible ways of supplying heat for cooking food

3 How would you supply the electricity needed for lighting, PCs and machinery?

4 There will be a refrigerator for life-saving medicines, as well as chemicals, that need to be stored at a constant temperature. How would you ensure a constant supply of electricity?

5 Which natural resource on the island should be conserved?

6 On a copy of the map, mark where you plan to locate buildings and the energy harvesters (devices that collect energy from the environment), showing how you would get the energy from the harvesters to the buildings, if necessary. Explain your reasons for choosing these particular sites.

7 Would your answers be different if the team had a limited budget? Explain your answer.

8 Describe what other information you might need before you can make a recommendation to the team.

Part 2

In a group of four, design your own island and a brief or set of questions for another group to decide how they will provide the required energy. Be prepared to answer questions and have your own solution in mind.

REFLECTION

Is there an effective method for memorising the different energy resources? For example, could you put them into categories? How will you learn their advantages and disadvantages?

ACTIVITY 7.3

Planning meeting

Work in a group of three. Each group will be randomly allocated a 'power station' that uses a different energy resource (such as a wind farm). You will be given the role of either advocating (supporting) or opposing planning permission for your allocated power station to be built close to your community

You will need to identify the general advantages or disadvantages of your power station before identifying the specific advantages or disadvantages of locating it close to your community

Each group will present their case as a spoken presentation, with a whiteboard and pens the only resources permitted

- You will be given a short time to agree, as a class, the criteria for judging each case. For example, you might decide to dismiss a case if the science is incorrect.
- You will then be allocated your power station. Unless it is given as a homework task (when you could spend time doing more detailed research), spend about five minutes in your groups preparing your case.
- Those advocating and opposing each power station will be called to the front of the class and each given a maximum of one minute to put their case to the rest of the class. The class will have a maximum of 30 seconds to question each case. While listening to each case, note down the advantages and disadvantages of each power station in a table so that you have a summary. Questions from the class and answers from your teacher should identify any errors
- While you are in the audience, you will score each presentation out of 10 according to the criteria agreed. Subtract your vote for the opposition from your vote for the advocates to get an overall score. Two examples are given in Table 7.1. A negative score suggests opposition but, if all proposals are negative, you might be forced to choose the least-worst option.

Type of power station	For	Against	Overall score
wind farm	2	4	−2
nuclear	7	3	4

Table 7.1: Example score sheet

Did you find Activity 7.3 helpful in summarising the advantages and disadvantages of the different energy resources? Is there a better method for learning this material?

water cycle: water evaporates from the surface of the Earth, rises into the atmosphere, cools, condenses, and falls as rain

nuclear fusion: the process by which energy is released when two small light nuclei join together to form a new heavier nucleus

7.2 Energy from the Sun

Most of the energy we use can be traced back to radiation from the Sun. To summarise:

- Fossil fuels are stores of energy that came from the Sun millions of years ago.
- Radiation (light and heat) from the Sun can be absorbed by solar panels to provide hot water. Sunlight can also be absorbed by arrays of solar cells (photocells) to generate electricity. In some countries, you may see these on the roofs of houses.
- The wind is caused when air is heated by the Sun. Warm air rises; cool air flows in to replace it. This moving air can be used to generate electricity using wind turbines.
- Most hydroelectric power comes ultimately from the Sun. The Sun's rays cause water to evaporate from the oceans and land surface. This water vapour in the atmosphere eventually forms clouds at high altitudes. Rain falls on high ground, and can then be trapped behind a dam. This is part of the water cycle. Without energy from the Sun, there would be no water cycle and no hydroelectric power.

However, we make use of a small amount of energy that does not come from the Sun as radiation. Here are three examples:

- The Moon and the Sun both contribute to the oceans' tides. Their gravitational pull causes the level of the ocean's surface to rise and fall every twelve-and-a-bit hours. At high tide, water can be trapped behind a dam. Later, at lower tides, it can be released to drive turbines and generators. Because this depends on gravity, and not the Sun's heat and light, we can rely on tidal power even at night and when the Sun is hidden by the clouds.
- Nuclear power makes use of nuclear fuels – mostly uranium – mined from underground. Uranium is a slightly radioactive element, which has been in the ground ever since the Earth formed, together with the rest of the Solar System, 4.5 billion years ago.
- Geothermal energy also depends on the presence of radioactive substances inside the Earth. These have been there since the Earth formed; they have been continuously releasing their store of energy ever since.

The source of the Sun's energy

The Sun releases vast amounts of energy, but it is not burning fuel in the same way as we have seen for fossil fuels. It is not a chemical reaction. The Sun consists largely of hydrogen, but there is no oxygen to burn this gas. Instead, energy is released in the Sun by the process of nuclear fusion. In nuclear fusion, four energetic hydrogen atoms collide and fuse (join together) to form an atom of helium.

Nuclear fusion requires very high temperatures and pressures. The temperature inside the Sun is close to 15 million degrees. The pressure is also very high, so that hydrogen atoms are forced very close together, allowing them to fuse. At this temperature all the atoms are ionised. All the electrons have been removed from all the atoms, creating plasma of positive nuclei and negative electrons. Atomic nuclei all have a positive charge and like charges repel so a temperature of about 100 million degrees (and high pressure) is required to overcome this electrostatic repulsion and get the nuclei close enough to fuse. The mass of the final nucleus is slightly less than the combined mass of the initial nuclei and the difference in mass is turned into energy according to Einstein's famous equation: $E = mc^2$. The energy, E, released is big because the mass, m, is multiplied by the speed of light, c, squared (which is a big number).

Nuclear fusion reactors – artificial Suns on Earth?

Scientists have been trying to recreate the same process artificially here on Earth since the 1950s as it offers a clean source of almost unlimited energy. It will not produce greenhouse gases or nuclear waste.

It is essential to hold the hot plasma in place for long enough for fusion to take place. In the Sun, the star's enormous gravitational field prevents the plasma escaping. In the 1950s, Soviet physicists came up with the idea of a tokamak (Figure 7.11) to contain the plasma.

Figure 7.11: China's new tokamak under construction in Chengdu

This is a container shaped like a torus (or doughnut) with a complicated arrangement of magnets to stop the plasma touching the walls. If the plasma were to touch the container walls, it would cool (and fusion would stop) and the container walls would be damaged. This is why fusion is a very challenging engineering problem.

Fusion reactors on Earth will fuse deuterium and tritium (two isotopes of hydrogen) to produce helium and a neutron. Only charged particles (that are moving) can experience a magnetic force and be confined by a magnetic field. Neutrons are neutral (have zero charge) so cannot be confined by the magnetic field and so they hit the walls of the tokamak. These collisions produce thermal energy. Heat exchangers in the walls conduct the thermal energy to heat up water to make steam to turn a turbine and produce electricity.

So far, no fusion reactor has produced more energy than needs to be put in to keep the plasma hot. In 1997 Joint European Torus claimed the world record for getting out 67% of the input energy. It is hoped that reactors will get out ten times more energy than is put in. The International Thermonuclear Experimental Reactor (ITER) project (Figure 7.12) is being built at Cadarache in France. This is an international collaboration that involves scientists from countries that represent half the world's population.

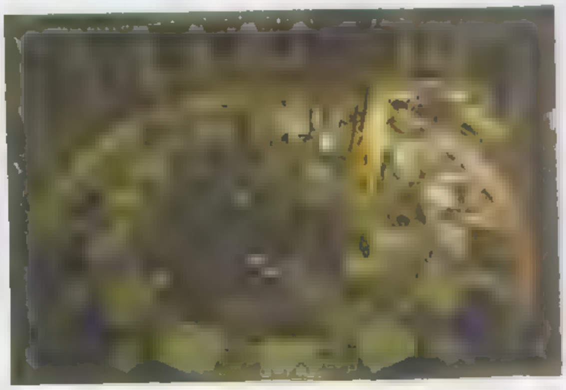


Figure 7.12: Employees in late 2018 building the tokamak inside the ITER (International Thermonuclear Experimental Reactor) construction site in France.

Questions

12 What is plasma?

13 Compare how plasma is confined in a star with how we will achieve the same effect here on Earth.

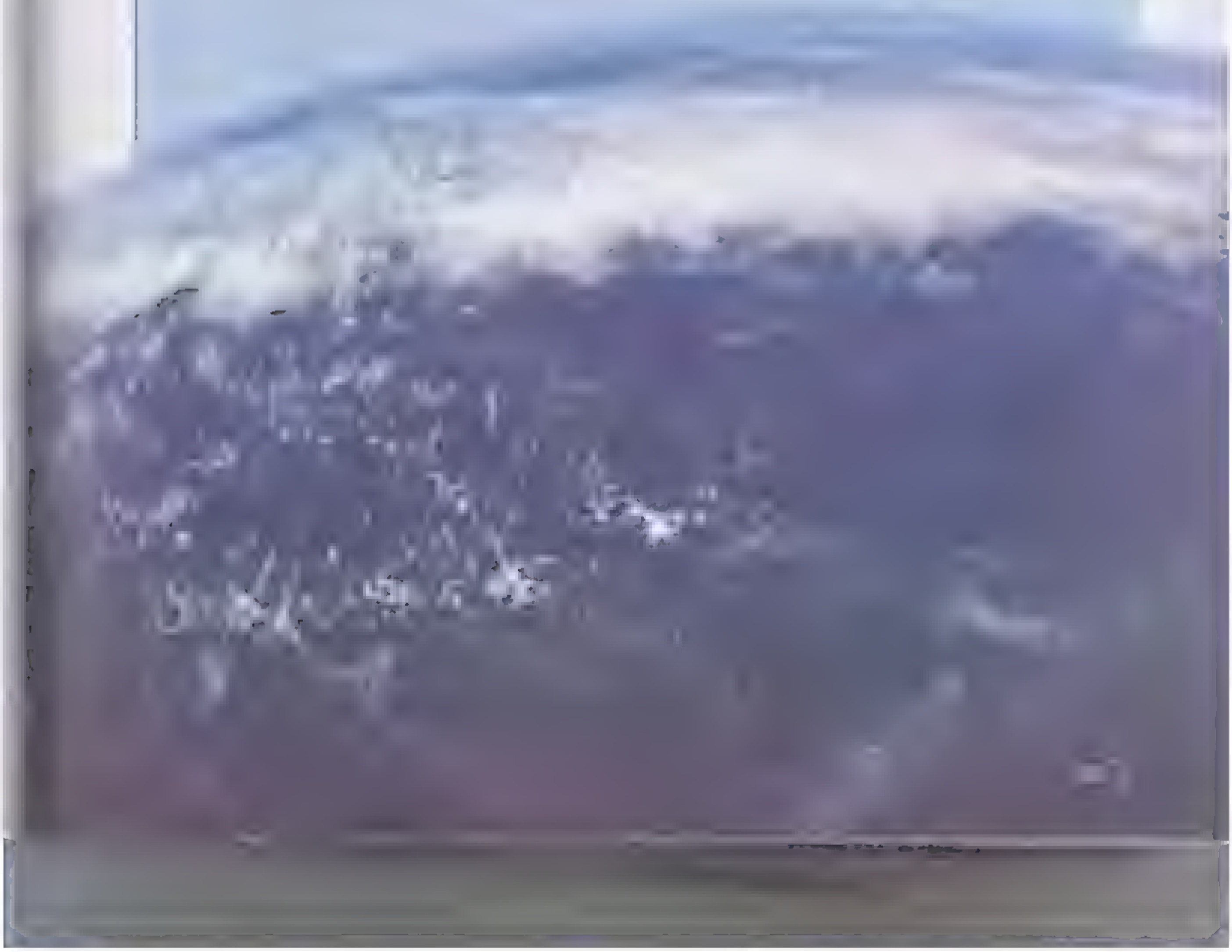
14 Discuss the advantages and disadvantages of nuclear fusion.

15 What is the difference between nuclear fusion and nuclear fission?

The future of energy resources

There is a huge variety of potential projects in this important area of physics We need energy but getting it by burning fossil fuels contributes to global warming. Whatever topic you choose, you need to pose a question like the one describing thorium reactors at the start of the chapter. Your answer should be clear, concise and coherent. Write it in your own words and limit yourself to 1000 words. Use informative diagrams where you can. Whatever medium you choose to convey your answer, try to reach an audience beyond your own classroom. Or, you could promote (for example, to your friends and family on social media) good work that you have discovered during your research. You could.

- Investigate ways to reduce demand for energy In cold countries this might include efforts to improve building insulation while, in hot countries, it might be worth thinking about the development of wind towers to reduce demand for air conditioning. Or you could focus on the development of more efficient transport (such as electric vehicles).
- Investigate ways to increase the supply of energy. This could focus on one of the energy resources you have already met in this chapter, or you might investigate one that is under development (for example, one based on algae).
- Investigate the challenges facing development of the lifters you met at the start of the chapter You should look at the process and make a comparison with nuclear power based on the uranium cycle.
- Investigate fracking. You should explain the process itself and offer a balanced assessment of the advantages and disadvantages.
- Investigate developments in energy storage, including improved battery technology, which might include the environmental impact of lithium mining.



Solar panels are used to collect energy from the Sun

Solar cells (also known as photocells) generate electricity using energy from the Sun

Oil, coal and natural gas are all examples of fossil fuels.

Coal forms from trees, and oil and natural gas form from microplankton.

Non-renewable energy resources will run out. This includes fossil fuels and nuclear fuel but not biofuel

Renewable energy resources are replenished (replaced) after they have been used

Biofuels are renewable, reliable, cheap to set up and use, but are diffuse

Geothermal energy is harvested (collected) where hot rock is close to the Earth's surface

Wind power, wave power and solar power are renewable but unreliable and dilute energy resources. Running costs are low but they are expensive to set up.

Hydroelectric power, tidal power and geothermal power are renewable, reliable and concentrated energy resources but suitable locations are limited, and they are expensive to set up.

Nuclear power stations use nuclear fuel, which produces thermal energy by nuclear fission when heavy nuclei break apart.

The Sun is the origin of all our energy resources except geothermal, nuclear and tidal.

The source of the Sun's energy is nuclear fusion, when hydrogen fuses (joins) together to form helium.

We are trying to develop nuclear fusion reactors.

1 Which of the following energy resources does **not** depend on sunlight? [1]

A hydroelectric power
B tidal
C coal
D wind

2 Which of the following energy resources produces greenhouse gases? [1]

A hydroelectric power
B nuclear
C biofuels
D natural gas

3 Which of these power stations generates electricity from gravitational potential energy? [1]

A tidal power station
B geothermal power station
C wind power
D nuclear power station

4 Which of these power stations generates electricity from thermal energy? [1]

A hydroelectric power station
B wind farm
C coal-fired power station
D solar farm

CONTINUED

5 Here is a list of energy resources available to the world. Some of these are renewable and some are non-renewable.

Energy resource	Non-renewable	Renewable
wave power		
hydroelectricity		
geothermal		
coal		
nuclear energy		
oil		
solar energy		
natural gas		
tidal energy		
wind energy		

Copy the table. In the first blank column, put a tick by any **three** resources that are non-renewable.

In the second blank column, put a tick by any **three** resources that are renewable. **[4]**

6 This question is about hydroelectric power stations. Water is stored behind a dam. Water released from the dam flows downhill and spins a turbine. The spinning turbine causes a generator to turn, which produces electricity

a Write down the **two** energy transfers that occur in a hydroelectric power station. **[1]**

b Explain how electricity from a hydroelectric power station relies on energy from the Sun. **[2]**

c The demand for electricity is not constant. Explain how a hydroelectric power station can help match supply to demand. **[2]**

[Total: 5]

7 A coal-fired power station and a wind turbine both produce electrical power. The power station produces 2500 MW and the wind turbine produces 2.0 MW.

a State one advantage of using wind turbines instead of a coal-fired power station to produce electricity. **[1]**

b Coal-fired power stations still account for one third of the world's energy consumption. Explain why wind turbines have not replaced them. **[2]**

[Total: 3]

8 An energy company is proposing a new power station but has to decide between a solar power station and a geothermal power station. Explain how the location and the climate might affect the decision. **[4]**

explain set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

state express in clear terms

CONTINUED

[illegible]

- [illegible] people die if they [illegible] [1]
- [illegible] might stop working [1]

[Total: 2]

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	Need[illegible] more work	Almos[illegible] there	Confident to move on
Appreciate that electricity is a convenient way of moving energy to where it is used.	7.1			
Recall all the energy resources: fossil fuels, biofuels, nuclear, geothermal, solar, hydroelectric, tidal, wind and wave.	7.1			
Describe how each energy resource can produce electricity or other useful forms of energy	7.1			
Give advantages and disadvantages of each energy resource in terms of renewability, cost, reliability, availability, scale and environmental impact.	7.1			
Understand that the Sun is the origin of all our energy resources except geothermal, nuclear and tidal	7.2			
Understand that nuclear fusion is the source of the Sun's energy	7.2			
Understand that there has been a lot of research into developing a nuclear fusion reactor.	7.2			

Chapter 8
Work and power

- learn that work done equals energy transferred or the force multiplied by the distance moved in the direction of the force
- relate power to work done and time taken
- calculate work done and power: $W = Fd = \Delta E$ and $P = \frac{\Delta E}{t}$

GETTING STARTED

What is the everyday meaning of 'work'? Do you know what the word 'work' means in physics?

What is the everyday meaning of 'power'? Do you know what the word 'power' means in physics?

THE MACHINE AGE

Scottish engineer, James Watt (Figure 8.1), developed the steam engine just over two centuries ago. It delivered the power for Britain to enter the industrial age. According to legend, Watt's first customer wanted a steam engine only if it could pump at least as much water from a well to his brewery as one of his horses. The brewer picked his strongest horse and worked him hard for eight hours. The horse pumped 33 000 lb (1 lb = 0.453592 kg) of water to a height of one foot (0.3048 metres) per minute; this is the origin of the unit of horsepower. As you will see, this is equivalent to about 750 watts. The watt, W, is the SI unit for power, named after James Watt. Long before steam power, humans developed mechanical machines to perform tasks that might otherwise be impossible (such as the ramp to build the pyramids). Electric motors have been developed since.

Discussion questions

1 What are the advantages and disadvantages of using steam power?

2 Can we produce power without any of the disadvantages of steam power?

3 The steam engine is a machine that changes thermal energy (from a difference in temperature) into mechanical work. What other machines are mentioned in this section, and what energy transfers take place?

Figure 8.1: The Golden Boys statue in the UK, which shows Matthew Boulton, James Watt (centre) and William Murdoch, who all played a part in improving the steam engine.

8.1 Doing work

Figure 8.2 shows one way of lifting a heavy object. Pulling on the rope raises the heavy box. As you pull, the force moves the box upwards.

To lift an object, you need a store of energy (as chemical energy, in your muscles). You give the object more gravitational potential energy (g.p.e.). The force is your means of transferring energy from you to the object. The name given to this type of energy transfer by a force is doing work

The more work that a force does, the more energy it transfers. The amount of **work done** is simply the amount of energy transferred:

work done = energy transferred

Figure 8.2: Lifting an object requires an upward force pulling against gravity. As the box rises upwards, the force also moves upwards. Energy is being transferred by the force to the box.

KEY WORDS

work done: the amount of energy transferred when one body exerts a force on another; the energy transferred by a force when it moves; work done = energy transferred

Three further examples of forces doing work are shown in Figure 8.3.

Mechanical or electrical work is equal to energy transferred. In this chapter, we are focussing on mechanical work. Electrical work is discussed in Chapter 18

How much work?

Think about lifting a heavy object, as shown in Figure 8.2. A heavy object needs a big force to lift it. The heavier the object is, and the higher it is lifted, the more its g.p.e. increases. This suggests that the amount of energy transferred by a force depends on two things:

- the size of the force – the greater the force, the more work it does
- the distance moved in the direction of the force – the further it moves, the more work it does.

So a big force moving through a big distance does more work than a small force moving through a small distance.

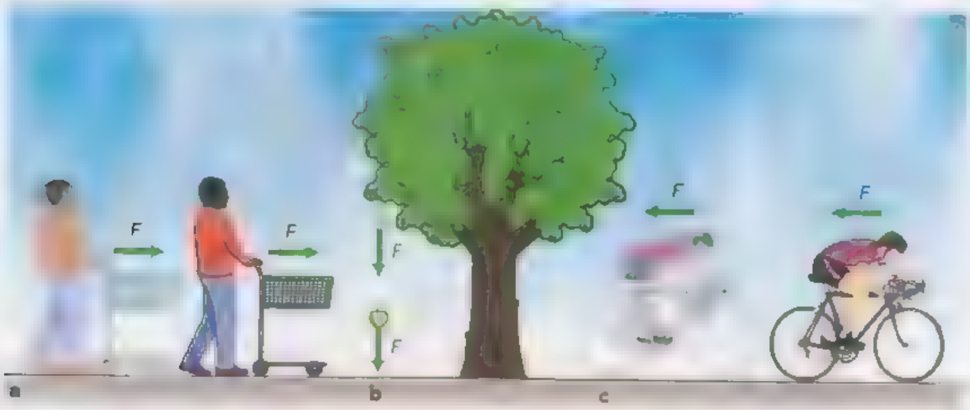


Figure 8.3: Three examples of forces doing work. In each case, the force moves as it transfers energy. **a:** Pushing a shopping trolley to start it moving. The pushing force does work. It transfers energy to the trolley, and the trolley's kinetic energy (k.e.) increases. **b:** An apple falling from a tree. Gravity pulls the apple downwards. Gravity does work, and the apple's k.e. increases. **c:** Braking to stop a bicycle. The brakes produce a force of friction, which slows down the bicycle. The friction does work, and the bicycle's k.e. is transferred to the internal energy of the brakes, which get hot.

Words in physics

You will by now understand that 'work' is a word that has a specialised meaning in physics, different from its meaning in everyday life. When physicists think about the idea of work, they think about forces causing movement.

If you are sitting thinking about your homework, no forces are causing movement and you are doing no work. It is only when you start to write that you are doing work in the physics sense. To make the ink flow from your pen, you must push against the force of friction, and then you really are working. Similarly, you are doing work (in the sense of physics) when you lift up this heavy book.

Many words have specialised meanings in science. In earlier chapters, we used these words: 'force', 'mass', 'weight', 'velocity', 'moment' and 'energy'. Each has a carefully defined meaning in physics. This is important because physicists have to agree on the terms they are using. However, if you look these words up in a dictionary, you will find that they have a range of everyday meanings, as well as their specialised scientific meaning. This is not a problem, provided you know whether you are using a particular word in its scientific sense or in a more everyday sense. (Some physicists get very upset if they hear shopkeepers talking about weights in kilograms, for example, but no-one will understand you if you ask for 10 newtons of oranges!)

8.2 Calculating work done

When a force does work, it transfers energy to the object it is acting on. The amount of energy transferred is equal to the amount of work done. We can write this as a simple equation:

$$W = \Delta E$$

In this equation, we use the symbol Δ (Greek capital letter delta) to mean 'amount of' or 'change in'. So,

$$\Delta E = \text{change in energy}$$

How can we calculate the work done by a force? The work done depends on two things:

- the size of the force, F
- the distance, d, moved by the force.

We can then write an equation for this:

work done by a force = force × distance moved by the force in the direction of the force.

In symbols:

$$W = Fd = \Delta E$$

work done by a force = force × distance moved by the force in the direction of the force

$$W = Fd = \Delta E$$

The phrase 'in the direction of the force' will be explained shortly. As amount of work done is the same as the amount of energy transferred, it is measured in joules (J), the unit of energy.

Joules and newtons

The equation for the work done by a force ($W = F \times d$) shows us the relationship between joules and newtons. If we replace each quantity in the equation by its SI unit, we get 1 J = 1 N × 1 m = 1 N m. So, a joule is a newton metre.

joule (J): the SI unit of transferred energy (or work done); work done is the force of one newton (1 N) when applied through a distance of one metre (1 m); 1 J = 1 N m

A crane lifts a crate upwards through a height of 20 metres. The lifting force provided by the crane is 5.0 kN, as shown in Figure 8.4.

a How much work is done by the force?

b How much energy is transferred to the crate?

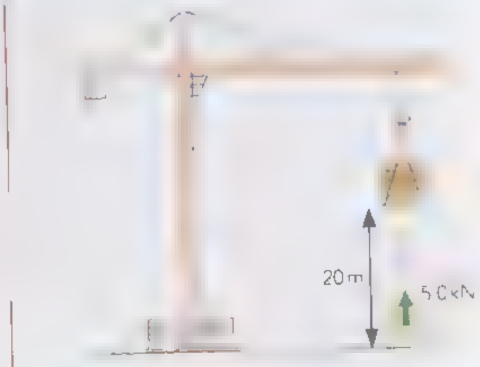


Figure 8.4

Step 1: Write down what you know, and what you want to know

$F = 5.0\,\text{kN} = 5000\,\text{N}$

$d = 20\,\text{m}$

$W = ?$

Step 2: Write down the equation for work done, substitute values and solve.

$W = F \times d = 5000\,\text{N} \times 20\,\text{m}$

$= 100\,000\,\text{Nm} \equiv 100\,000\,\text{J}$

Answer

a The work done by the force is 100 000 J, or 100 kJ

b Since work done = energy transferred, 100 kJ of energy is transferred to the crate.

Work done and *mgh*

Worked Example 8.1 illustrates an important idea. The force provided by the crane to lift the crate must equal the crate's weight, mg. It lifts the crate through a height, h. Then the work it does is force × distance, or $mg \times h$. The gain in g.p.e. of the crate is mgh. This explains where the equation for g.p.e. comes from.

In Figure 8.5, the child slides down the ramp. Gravity pulls her downwards, and makes her speed up. To calculate the work done by gravity, we need to know the vertical distance, h, because this is the distance moved in the direction of the force. If we calculated the work done as weight × distance moved down the ramp, we would get an answer that was too large. Now you should understand why we write the definition of work done like this:

work done = force × distance moved in the direction of the force

Figure 8.5: It is important to use the correct distance when calculating work done by a force. Gravity makes the child slide down the slope. However, to calculate the energy transferred by gravity, we must use the vertical height moved

Forces doing no work

If you sit still on a chair (Figure 8.6), there are two forces acting on you. These are your weight, mg, acting downwards, and the upward contact force, C, of the chair, which stops you from falling through the bottom of the chair.

Neither of these forces is doing any work on you. The reason is that neither of the forces is causing movement, so you do not move through any distance, d. From $W = F \times d$, the amount of work done by each force is zero. When you sit still on a chair, your energy does not increase or decrease as a result of the forces acting on you.

Figure 8.6: When you sit still in a chair, there are two forces acting on you. Neither transfers energy to you.

Figure 8.7 shows another example of a force that is doing no work. A spacecraft is travelling around the Earth in a circular orbit. The Earth's gravity pulls on the spacecraft to keep it in its orbit. The force is directed towards the centre of the Earth. However, since the spacecraft's orbit is circular, it does not get any closer to the centre of the Earth. There is no movement in the direction of the force and so gravity does no work. The spacecraft continues at a steady speed (its k.e. is constant) and at a constant height above the Earth's surface (its g.p.e. is constant). Of course, although the force is doing no work, this does not mean that it is not having an effect. Without the force, the spacecraft would escape from the Earth and disappear into the depths of space.

Figure 8.7: The spacecraft stays at a constant distance from the Earth. Gravity keeps it in its orbit without transferring any energy to it.

A girl can provide a maximum pushing force of 200 N. To move a box weighing 400 N onto a platform, she uses a plank as a ramp, as shown in Figure 8.8.

a How much work does she do in raising the box?

b How much g.p.e. does the box gain?

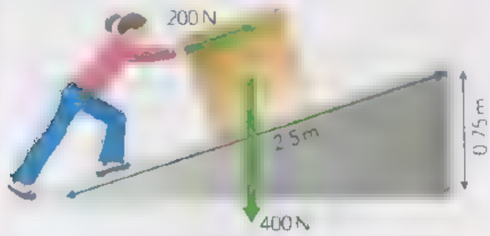


Figure 8.8

Step 1: Write down what you know, and what you want to know.

pushing force along the ramp $F = 200$ N
distance moved along ramp $d = 2.5$ m
weight of box downwards $mg = 400$ N
vertical distance moved $h = 0.75$ m
work done along the ramp $W = ?$
work done against gravity $W' = ?$

Step 2: Calculate the work done, W, by the pushing force along the ramp.

W = pushing force along ramp × distance moved along ramp
$= F \times d$
$= 200\ \text{N} \times 2.5\ \text{m}$
$= 500\ \text{J}$

Step 3: Calculate the gain in g.p.e. of the box. This is the same as the work done against gravity, W'.

W' = weight of box × vertical distance moved
$= mg \times h$
$= 400\ \text{N} \times 0.75\ \text{m}$
$= 300\ \text{J}$

Answer

a The girl does 500 J of work in raising the box.

b The box gains 300 J in g.p.e.

Note: only 300 J is transferred to the box. The remaining 200 J is the work done against friction as the box is pushed along the slope.

ACTIVITY 8.1

The efficiency of a ramp

The Ancient Egyptians are famous for their pyramids. The pyramids are made from stone blocks with a mass of at least one tonne. The useful work done in lifting a block is the weight of the block multiplied by the vertical distance it is moved. Whether the block is dragged or lifted, work has to be done against the force of gravity.

The Ancient Egyptians did not have cranes. It is believed they used ramps to drag the blocks into place. The ramp is an example of a simple machine. It reduces the required force (sometimes called the effort) but this force has to be applied over a bigger distance than if it were moved vertically. If there was no friction, the ramp would be 100% efficient. However, additional work needs to be done against friction.

Your task is to design an experiment to work out how the efficiency of a ramp depends on the angle of the slope.

You need to recall what efficiency is and how to calculate it.

You need to decide on:

- the equipment you will need (sketch a labelled diagram of your assembled apparatus)
- your independent, dependent and control variables (that is, what you will change, what you will measure and what you will keep the same)
- the measurements that you will take (design a table to record them)
- what you need to calculate (what equations you will need)
- the graph that you will plot and predict what your graph should look like.

Then join together to form design teams of three. First, peer assess each other's work. Then develop a combined plan, putting together the best of the individual plans.

Discuss your plan with a neighbouring group and be prepared to share your ideas with the class.

PEER ASSESSMENT

When you check the plan in Activity 8.1, go through this list.

- Does the plan include the correct equipment? Is anything missing?
- Does the plan include a clear sketch of the experimental setup?
- Are the independent, dependent and control variables identified correctly?
- The experiment requires that one end of the ramp is raised. Is there a sensible range of heights? Does the plan explain how the angle of the slope is calculated?
- Does it suggest repeating measurements so that an average value of the dependent variable can be calculated for each value of the independent variable?
- Does the plan explain how to do any calculations?
- Does the plan explain what to plot on each axis of the graph?
- Does the plan predict what the graph should look like?
- Can you carry out the experiment successfully based on what your classmates have written?

Improve your own work using the feedback on it from another group.

Questions

1 Explain why no work is being done by the Sun's gravity on the Earth.

2 A boy pulls a sled (at a constant speed) with a force of 50 N for a distance of 250 metres.
How much work does the boy do?

3 A 100 g apple falls from a tree and lands on the ground 6 metres below.

   a What is the force that is pulling the apple, and how large is the force?

   b Calculate how much work gravity does on the apple as it falls.

   c What energy transfer is taking place?

4 A man is trying to move his washing machine into the back of a removal van. The washing machine has a weight of 650 N and the floor of the removal van is 0.80 metres above the ground (Figure 8.9).

Figure 8.9: Moving a washing machine

   a Calculate the work the man does when he pushes the washing machine up the ramp into the back of the van against a frictional force of 440 N.

   b Superman happens to be passing and he lifts the washing machine vertically into the van (without using the plank). Calculate the work Superman does.

   c Explain why a and b give different answers.

   d Calculate the efficiency of the ramp.

8.3 Power

Exercising in the gym (Figure 8.10) can put great demands on your muscles. Speeding up a treadmill means that you have to work harder to keep up. Equally, your trainer might ask you to find out how many times you can lift a set of weights in one minute. These exercises are a test of how powerful you are. The faster you work, the greater your power.

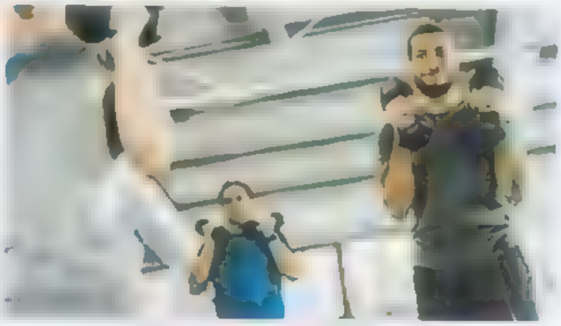


Figure 8.10: At the gym, it is easier to lift small loads, and to lift them slowly. The greater the load you lift and the faster you lift it, the greater the power required. It is the same with running on a treadmill. The faster you have to run, the greater the rate at which you do work.

In physics, the word power is used with a special meaning. It means the rate at which you do work (that is, how fast you work). The more work you do, and the shorter the time in which you do it, the greater your power. Power is the rate at which energy is transferred, or the rate at which work is done.

power: the rate at which work is done, or the rate at which energy is transferred

Fast working

Power tells you about the rate at which a force does work, that is the rate at which it transfers energy. When you lift an object up, you are transferring energy to it. Its potential energy increases. You can increase your power by

- lifting a heavier object in the same time
- lifting the object more quickly

It is not just people who do work. Machines also do work, and we can talk about their power in the same way

- A crane does work when it lifts a load. The bigger the load and the faster it lifts the load, the greater the power of the crane.
- A locomotive pulling a train of coaches or wagons does work. The greater the force with which it pulls and the greater the speed at which it pulls, the greater the power of the locomotive.

Question

5 Your neighbour is lifting bricks and placing them on top of a wall. He lifts them slowly, one at a time. State two ways in which he could increase his power (the rate at which he is transferring energy to the bricks).

8.4 Calculating power

We know from Section 8.3, that power is the rate at which work is done. Since work done is equal to energy transferred, we can write these ideas about power as equations, as shown.

$$\text{power} = \frac{\text{work done}}{\text{time taken}} \qquad \text{power} = \frac{\text{energy transferred}}{\text{time taken}}$$

$$p = \frac{W}{t} \qquad p = \frac{\Delta E}{t}$$

The meaning of work and power

Work and power have very specific meanings in physics. You will create a resource that helps people understand their correct meanings in physics. You could start by collecting definitions that are wrong in physics. For example, collect images of powerful people or cars, or an image of a gymnast performing the 'iron cross' (Figure 8.11). If you are feeling creative, you could write a poem or create a song or podcast.

- Work for a few minutes in small groups to discuss ideas and choose one idea to develop.
- Develop your idea within the timeframe given by your teacher.
- If the class is divided into two or three large groups, you will perform or present your idea to the other pairs or threes in your group.
- Vote on the other presentations. A pair or three cannot represent their group unless the physics is correct so help correct any physics mistakes
- The pair or three chosen by each group will present to the rest of the class.

Figure 8.11: This gymnast is performing the 'iron cross' on rings. It is a move that requires tremendous strength in the core, arms and wrists. But is he doing any work from a physics point of view?

Units of power

Power is measured in watts (W). One watt (1 W) is the power when one joule (1 J) of work is done per unit time. So one watt is one joule per second.

- 1 W = 1 J/s
- 1000 W = 1 kW (kilowatt)
- 1 000 000 W = 1 MW (megawatt)

Take care not to confuse *W* for work done (or energy transferred) with W for watts. In books, the first of these is shown in italic type (as here), but you cannot usually tell the difference when they are handwritten. SI units are often related to each other. It is useful to remember some of the connections, such as 1 J = 1 N m and 1 W = 1 J/s.

watt (W): the unit of power when 1 J of work is done per unit time; 1 W = 1 J/s

Power in general

We can apply the idea of power to any transfer of energy. For example, electric light bulbs transfer energy supplied to them by electricity. They transfer energy by light and heating. Most light bulbs are labelled with their power rating – for example, 40 W, 60 W, 100 W – to tell the user about the rate at which the bulb transfers energy.

We can express the efficiency of a light bulb or any other energy-changing device in terms of the power it supplies:

$$\text{percentage efficiency} = \frac{\text{useful power output}}{\text{power input}} \times 100\%$$

Remember, from Chapter 6, how this compares with the equation for energy efficiency in terms of energy

$$\text{percentage efficiency} = \frac{\text{useful energy output}}{\text{energy input}} \times 100\%$$

There is more about electrical power in Chapter 18.

A car of mass 800 kg accelerates from rest to a speed of 25 m/s in 10 s. What is its power?

Step 1: Calculate the work done. This is the increase in the car's kinetic energy.

$$\text{k.e} = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 800\,\text{kg} \times (25\,\text{m/s})^2$$

$$= 250\,000\,\text{J}$$

Step 2: Calculate the power

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$

$$= \frac{250\,000\,\text{J}}{10\,\text{s}}$$

$$= 25\,000\,\text{W} \equiv 25\,\text{kW}$$

Answer

The energy is being transferred to the car (from its engine) at a rate of 25 kW, or 25 kJ per second.

Car engines are not very efficient. In this example, the car's engine may transfer energy at the rate of 100 kW or so, although most of this is wasted as thermal energy

Do you find the problem-solving strategy in the worked examples useful?

Do you use it all the time?

Do you have a better approach?

Questions

6 **a** How many watts are there in a kilowatt?

b How many watts are there in a megawatt?

7 One horsepower is the power output of one horse when it lifts a mass of 33 000 lb of water through a height of one foot in one minute as shown in Figure 8.12

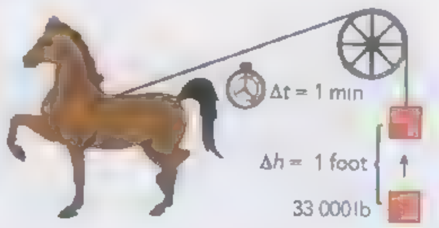


Figure 8.12: A graphical representation of horse power

You need to know that 1 lb = 0.453592 kg and one foot = 0.3048 metres.

a Calculate the mass of water the horse lifts in one minute.

b Calculate the weight of water the horse lifts in one minute. (Assume that g = 10 N/kg)

c Calculate the work the horse does in one minute.

d Calculate the power output of the horse.

8 An average man needs to eat food containing about 2500 kcal of chemical potential energy per day (1 kcal = 4.18 kJ).

a What is 2500 kcal expressed in joules?

b Calculate the power output of the average man, even when he is doing no work.

9 It is estimated that the human brain has a power requirement of 40 W. How much energy does it use in an hour?

10 A light bulb transfers 1000 J of energy in 10 s. What is its power?

11 An electric motor transfers 100 J in 8.0 s. It then transfers the same amount of energy in 6.0 s. Has its power increased or decreased?

ACTIVITY 8.3

What is the power of a world-class sprinter?

Work on this problem on your own for three minutes. Share your ideas with a partner for a further two minutes. Be prepared to share your results and thinking with the rest of the class.

The 100 metre sprint world record of 9.58 seconds was set in the final of the World Athletics Championships in Berlin in 2009.

- Work out the average speed for a sprinter running 100 m in 9.58 s.
- Using the average speed, work out the sprinter's kinetic energy for the race. Assume that he had a mass of 86 kg.
- Work out his power output.

This power output is much smaller than the figure worked out by a team of Mexican scientists. They worked out that he had a maximum power output of about 2600 W and his total mechanical work was 80 kJ.

- What is missing from your calculation?
- Apart from the fact that he did not run at a constant speed, are there any other assumptions you made in your calculation?
- To reach a more realistic value, think about the forces involved when he is accelerating and even when he is running at a constant speed.

ACTIVITY 8.4

Revision boomerang

You will be in a group of three. Your teacher will let you know how much time you have to draw a mind map on a sheet of A3. It should include all the key terms, concepts and equations related to energy (from Chapters 6, 7 and 8). Use pictures to illustrate the ideas where possible, but your mind map should include:

- the principle of conservation of energy and the various energy stores and energy transfers
- the various energy resources (which ones depend on sunlight, which are renewable, and so on)
- any equations (both word and symbol) you need to know (include units in pencil or a different colour)

When your teacher tells you to, pass your mind map to the person on your left. You receive a mind map from the person on your right. Your job is to correct any mistakes and add missing information.

When your teacher tells you, the mind maps will change hands a second time. Correct and add as before.

The next time your teacher asks you to pass on the mind maps, your own mind map should arrive back with you.

SELF ASSESSMENT

Did you know most of the information for Activity 8.4, or did your classmates need to add a lot of missing information?

If you could not remember as much as you thought you would, you need to develop a strategy to help you learn the material (for example, by developing a set of flash cards).

How does the stopping distance of a vehicle vary with its speed?

Figure 8.13: A collision between a car and a crash test dummy in order to raise awareness of road safety

You are going to apply some of the physics you have learned to keep you and other motorists safer. Table 8.1 shows how the stopping distance for an emergency stop is affected by the speed of the car. An emergency stop is when a driver attempts to stop in the shortest possible distance in order to avoid an accident.

Note that stopping distance = thinking distance + braking distance. The driver cannot apply the brakes instantly. Thinking distance is the speed of the car multiplied by the driver's reaction time. This is the distance travelled between the driver becoming aware of a hazard and applying the brakes.

Speed / m/s	Thinking distance / m	Braking distance / m	Stopping distance / m
8.9	6	6	12
13.4	9	14	23
17.9	12	24	36
22.3	15	38	53
26.8	18	55	73
31.3	21	75	96

Table 8.1: Stopping distances for different speeds

When a car comes to an emergency stop all its kinetic energy is transformed into thermal energy because of the work done by the brakes, W, which apply a braking (frictional) force, F, throughout the braking distance. So, $W = Fd$, where F is the frictional force and d is the stopping distance. We can write: $\frac{1}{2}mv^2 = Fd$.

1. Assume that the mass of the car is 1500 kg and the braking force is 10 000 N. Show that you get nearly the same braking distance as in Table 8.1.
2. Find the guidelines published in your country. Though the physics is the same, different assumptions might have been made to arrive at different numbers. If you know how to, develop a spreadsheet so that calculations for the different speeds can be done at the same time.
3. What could reduce the braking force?
4. Work out the braking distance when the braking force is halved.
5. Work out the reaction time for the thinking distances in Table 8.1.
6. Work out the thinking distance when the thinking time is doubled.
7. List the ways in which reaction time for a driver could increase.
8. Design one of two safety campaign posters. Use physics (and graphs) to back up your claims.
   - Design a poster urging people to drive more slowly. A longer stopping distance reduces the chance that an accident can be avoided and increases the impact speed. Emphasise that damage (and injuries) depends on the kinetic energy of the car, not its speed.
   - Design a safety campaign poster urging people not to use their phone when driving as it could increase their reaction time.

Energy transferred by a force is called work done.
The amount of work done is the amount of energy transferred.
The amount of work done depends on the size of the force – the greater the force, the more work is done.
The amount of work done depends the distance moved in the direction of the force – the further it moves, the more work is done.
To calculate the energy transferred by the force of gravity, we must use the vertical height moved.
Work done = force × distance in the direction of the force.
The work done to move a weight vertically upwards is equal to g.p.e.
Power is the rate at which energy is transferred, or the rate at which work is done.
Power can be increased by increasing the work done in a given time.
Power can be increased by reducing the time over which the same work is done.
Recall and use the equation $P = \frac{\Delta E}{t}$ in simple systems.

EXAM-STYLE QUESTIO

1 Work done is measured in which of the following units? **[1]**

A newton **B** watt **C** kilogram **D** joule

2 Power is measured in which of the following units? **[1]**

A newton **B** watt **C** kilogram **D** joule

3 A man pushes a 25 kg pram up a slope as shown in the diagram.

He pushes with a force of 150 N along the 20 m slope. How much energy is dissipated as thermal energy? **[2]**

A 250 J **B** 500 J **C** 2000 J **D** 2500 J

4 For each sentence, select the correct word from the list.

work energy more less

a When it moves an object, a smaller force does _______ work than a bigger force. [1]

b The greater the distance an object is moved by the force, the ______ work it does. [1]

c Power is the rate at which ______ is transferred. [1]

d Power is the rate at which ______ is done. [1]

[Total: 4]

5 The Empire State Building in New York is the venue for an annual running competition. Competitors race up 86 floors (1576 stairs) or 320 metres to finish close to the top. The record fastest time is 9 minutes 33 seconds by Paul Crake in 2003. His mass was 62.5 kg

a Calculate Paul Crake's weight. [1]

b State the relationship between work done, force and distance. [1]

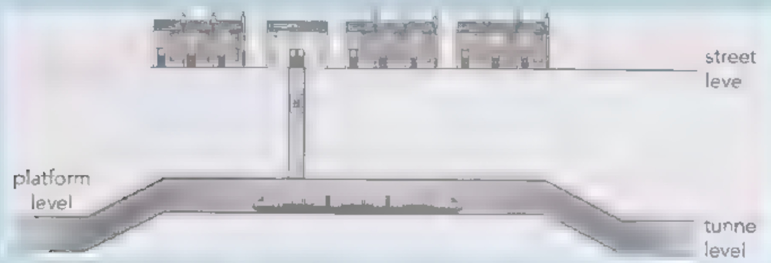
c Calculate the work done by Paul Crake. Express your answer in kJ (1 kJ – 1000 J). [2]

d State the relationship between power, work done, and time. [1]

e Calculate Paul Crake's average power output during his record-breaking run. [2]

[Total: 7]

6 a The diagram shows a section through a subway station. The track at the station platform is designed to be higher up than the track in the tunnels. The driver uses brakes to stop the train at the platform and a motor to make the train set off. What is the advantage of having the platform higher up than the track in the tunnels? Explain your answer in terms of the work done by the brakes and the motor. [2]



b A subway train has a mass of 270 000 kg (including passengers) and a maximum kinetic energy of 81.7 MJ

i State the relationship between kinetic energy (k.e.), mass and velocity. [1]

ii Calculate the maximum velocity of the train. [3]

[Total: 6]

calculate: work out from given facts, figures or information

state: express in clear terms

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	See Topic...	Needs more work	Almost there	[illegible]
Understand that work done equals energy transferred	8.1			
Relate work done to the force multiplied by the distance moved in the direction of the force	8.2			
Recall and use $W = Fd = \Delta E$.	8.2			
Understand the relationship between power, work done and time	8.3			
Recall and use the equation $P = \frac{\Delta E}{t}$ for simple problems.	8.3			

› Chapter 9

The kinetic particle model of matter

- describe the three states of matter (solid, liquid and gas)
- investigate changes of state
- use the kinetic model to explain changes of state and the behaviour of gases

Work with a partner. Take a large sheet of paper and write the words 'solid', 'liquid' and 'gas' on the paper.

Around each word, write as much as you can about that state of matter. You can include drawings.

Using a different coloured pen, make as many links as you can between the three words.

Figure 9.1: Making links between words

MELTING ICE LEADS TO MAGMA FLOW

Figure 9.2: Scientists in Arizona and Oxford have shown a correlation between the melting of glaciers and an increase in volcanic eruptions such as this one in Iceland which erupted in 2010

The volcano in Figure 9.2 is erupting. High temperatures inside the earth have melted the rock creating magma. Scientists believe the eruption may have been triggered by the melting of the glacier situated above the volcano. The glacier melting meant there was less ice pressing down on the rocks. This reduced the pressure on the magma underneath the rocks. This made it easier for magma to flow. The melting of the glaciers is linked to global warming, which is caused by the changes to gases in the atmosphere. Changes of state, such as the melting of glaciers, can have dramatic effects.

We are familiar with the changes that happen when ice melts. A glass-like solid changes into a transparent, colourless, runny liquid. Heat the liquid and it 'vanishes' into thin air. Although this sounds like a magic trick, it is so familiar that it does not surprise us. It is more surprising when we see solid rock heat up and become magma.

In this chapter, we will look at materials and their different states – solid, liquid and gas. We will consider how the particles in matter behave and how this can help us explain some of the things we observe when materials change from one state to another.

Discussion questions

1. List ten solids, ten liquids and ten gases. Are there any substances which are hard to categorise?
2. The Earth is distinctive among the planets of the Solar System in being the only planet on which water is found to exist naturally in all three of its physical states. Discuss how life on Earth would be affected if one of the states of matter did not exist.

9.1 States of matter

	 **Figure 9.3:** Ice cubes have a fixed shape	 **Figure 9.4:** This coloured water takes the shape of the flasks	 **Figure 9.5:** The steam leaving the pot quickly condenses to form water droplets
State	solid	liquid	gas
Size	rigid, fixed shape, fixed volume; cannot be squashed	not rigid, no fixed shape, fixed volume; cannot be squashed	not rigid, no fixed shape, no fixed volume; can be squashed
Shape	takes the shape of its container	takes the shape of its container	expands to fill its container

Table 9.1: The distinguishing properties of the three states of matter.

Matter exists in three states: solid, liquid and gas. An example of this is water which can exist as solid ice, liquid water or steam which is an invisible gas. Steam quickly condenses in air to form tiny water droplets, which are what we see. We can describe these states by describing their shape and volume (size). Table 9.1 shows how these help us to distinguish between solids, liquids and gases.

Figure 9.6: The volume of a liquid stays the same.

Figure 9.6 shows a famous psychology experiment. A young child will usually think the taller glass holds more water even when they see it being poured from the wider glass. The child does not realise yet that a liquid has a fixed volume. Although the drink changes its shape when you pour it from one glass to the other, its volume stays the same.

Changes of state

Heat a solid and it melts to become a liquid. Heat the liquid and it boils to become a gas. Cool the gas and it becomes first a liquid and then a solid. These are **changes of state**. The names for these changes are shown in Figure 9.7.

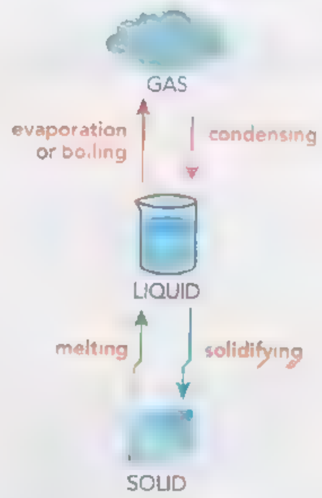


Figure 9.7: Naming changes of state

Another word for a liquid changing to a gas is evaporation. We will see the difference between evaporation and boiling later

KEY WORDS

states of matter: solid, liquid or gas

changes of state: changing from one state of matter to another

evaporation: changing from a liquid to a gas at any temperature

boiling: changing from liquid to gas at a fixed temperature called the boiling point

melting: changing from solid to liquid

condensing: changing from gas to liquid

solidifying/freezing: changing from liquid to solid

Questions

1 Copy and complete these sentences

The three states of matter are ____, ____ and ____

A solid has a definite shape and ____. A liquid has a definite ____ but takes the shape of its container. A gas will expand to fill all the ____ available.

When a solid is heated it ____ to make a ____. The temperature this happens at is called the ____.

The boiling point is the temperature at which a ____ turns to a ____.

2 a What name is given to the temperature at which a gas condenses to form a liquid?

b What name is given to the process during which a liquid changes into a solid?

c What name is given to the temperature at which this happens?

3 To measure the volume of a liquid, you can pour it into a measuring cylinder. Measuring cylinders come in different shapes and sizes – tall, short, wide, narrow. Explain why the shape of the cylinder does not affect the measurement of volume.

9.2 The kinetic particle model of matter

In this section, we will use a **model** to help us explain the behaviour of materials. Scientists often use models to explain things which we cannot see directly. Using this model will help us answer questions such as:

- why does an ice cube change shape as it melts?
- how can we smell perfume from across a room?
- why does it take time to melt a solid?

The model is called the **kinetic particle model of matter**. The word 'kinetic' means related to movement. All matter is made up of tiny particles – **atoms**, **molecules** or ions. When a substance is heated, its particles gain energy and move faster. The higher the temperature, the faster the particles move.

KEY WORDS

model: a way of representing a system which we cannot experience directly

kinetic particle model of matter: a model in which matter consists of moving particles

atom: the smallest part of an element that can exist

molecule: two or more atoms joined together by chemical bonds

There are many different types of particles with different chemical properties. In this chapter we will look at how these particles move rather than how they react. We will draw all the atoms and molecules as spheres and refer to them all as particles.

Figure 9.8a: Air is a mixture of elements and compounds

Figure 9.8b: For this model we will assume all atoms and molecules are identical spherical particles

The idea that matter is made up of identical, spherical molecules is a great simplification, but using this model will help to explain the behaviour of materials.

Describing the particle structure of solid, liquids and gases

Figure 9.9 shows how we picture the particles in a solid, a liquid and a gas. Each state of matter can be described by describing the arrangement, separation and motion of its particles.

Particle movement and temperature

Kinetic theory uses the idea that as particles heat up they gain more kinetic energy and so move faster. As a substance cools down its particles lose kinetic energy and slow down. This suggests that there is a theoretical lower limit to how cold anything can be. If the particles lose all their kinetic energy and stop moving, it is not possible for the substance to cool any further.

The lowest possible temperature anything can reach is −273 °C. This is also known as absolute zero.

KEY WORDS

absolute zero: the temperature at which particles have no kinetic energy

Figure 9.9: Representations of **a:** gas, **b:** liquid, **c:** solid. The arrangement, separation and motion of the particles change as the gas cools to become a liquid and then a solid

State	Arrangement and separation of particles	Motion of particles
Solid	The particles are packed closely together, in a regular pattern. Notice that each particle is in close contact with all its neighbours.	Because the particles are so tightly packed, they cannot move around. However, they do move a bit. They can vibrate about a fixed position. The hotter the solid, the more they vibrate
Liquid	The particles are packed slightly less closely together than in a solid. The particles are arranged randomly rather than in a fixed pattern.	Because the particles are slightly less tightly packed than in a solid, they can move around. So the particles are both vibrating and moving from place to place. The hotter the liquid is, the faster its molecules move.
Gas	The particles are widely separated from one another. They are no longer in contact, unless they collide with each other. In air, the average separation between the particles is about ten times their diameter	The particles move freely about, bouncing off one another and off the walls of the container. In air at room temperature, the average speed of the particles is about 500 m/s and this increases with temperature.

Table 9.2: The arrangement and motion of particles in the three different states of matter. Compare these statements with the diagrams shown in Figure 9.9

Evidence for the kinetic model

Atoms and molecules are far too small to see, even with a microscope, but experiments show the effects of moving atoms and molecules. These experiments do not prove there are moving particles, but they do provide support for the idea.

In 1827, a scientist called Robert Brown was using a microscope to study pollen grains when he noticed tiny particles jiggling about. At first he thought that they might be alive, but when he repeated his experiment with tiny grains of dust suspended in water, he saw that the dust also moved around. This motion is now known as **Brownian motion**, and it happens because the moving particles are constantly knocked about by the fast-moving particles of the air.

Brownian motion: the motion of small particles suspended in a liquid or gas, caused by molecular bombardment

observations: what you see happening in an experiment

We can do a similar experiment using smoke particles. The oxygen and nitrogen molecules that make up the air are far too small to see, so we have to look at something bigger, and look for the effect of the air molecules.

We can use a smoke cell (Figure 9.10a). This is a small glass box which contains air with a small amount of smoke. The cell is lit from the side, and the microscope is used to view the smoke particles.

The smoke particles show up as tiny specks of light, but they are too small to see any detail of their shape. What is noticeable is the way they move. If you watch a single particle, you will see that it follows random path, frequently changing direction. This is because air molecules repeatedly hit the smoke particle.

Explanations using the kinetic model

The kinetic model of matter can be used to explain many **observations**. Here are some of them

- Liquids take up the shape of their container because their particles are free to move about within the liquid.
- Gases fill their container because their particles can move about with complete freedom.
- Solids keep their shape because the particles are packed tightly together.
- Gases diffuse (spread out) from place to place, so that, for example, we can smell perfume across the room. The perfume particles spread about because they are free to move.

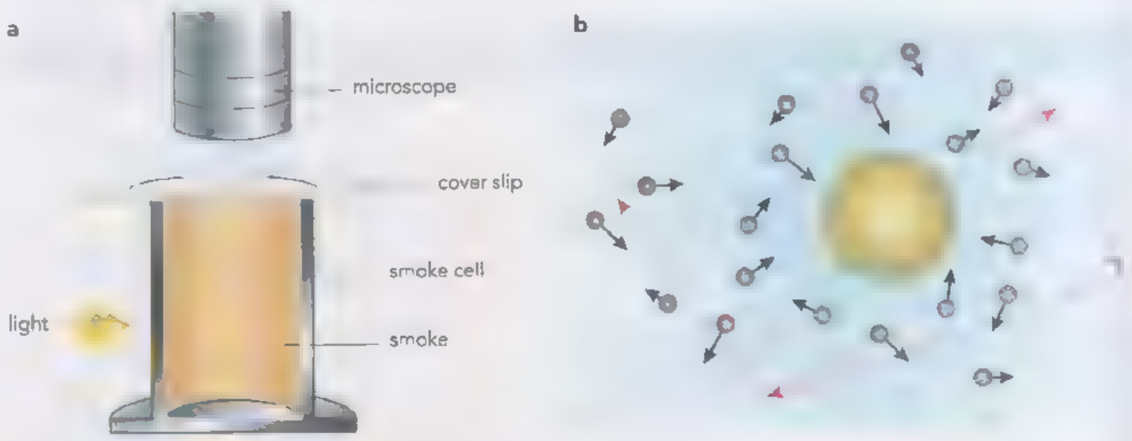


Figure 9.10a: An experimental arrangement for observing Brownian motion. The smoke particles are just large enough to show up under the microscope. The air molecules that collide with them are much too small to see. **b:** The invisibly small air molecules repeatedly hit the smoke particle making it change direction. The dotted line shows the path of the smoke particle

- Dissolved substances diffuse throughout a liquid. Sugar crystals in a drink dissolve and molecules spread throughout the liquid, carried by the mobile particles. In a hotter drink, the particles are moving faster and the sugar diffuses more quickly.
- Most solids expand when they melt. The particles are slightly further apart in a liquid than in a solid
- Liquids expand a lot when they boil. The particles of a gas are much further apart than in a liquid. We can think about this the other way round. Gases contract a lot when they condense. If all of the air in the room you are now in was cooled enough, it would condense to form a thin layer of liquid, two or three millimetres deep, on the floor.

More on Brownian motion

The molecules in air have an average diameter of about 4×10^{-10} metres. This makes them impossible to see with a laboratory microscope. The smoke particles consist of many molecules and so are many times larger than the air molecules. A smoke particle has a diameter of about 1×10^{-7} metres, which is about 250 times the diameter of the air molecules. The air molecules are light but fast moving and so have enough kinetic energy to cause the smoke particles to change direction on impact

Forces and the kinetic model

We have seen that the kinetic model of matter can explain the differences between solids, liquids and gases. We can explain some other observations if we add another scientific idea to the kinetic theory: we need to consider the forces between the particles that make up matter

Why do the particles that make up a solid or a liquid stick together? There must be **attractive forces** (forces pulling them together) between them. Without attractive forces to hold together the particles, there would be no solids or liquids, only gases. No matter how much we cooled matter down, it would remain as a gas.

Another way to refer to these forces is to say that there are **bonds** between the particles. Each particle of a solid is strongly bonded to its neighbours. This is because the forces between particles are strongest when the particles are close together. In a liquid, the particles are slightly further apart and so the forces between them are slightly weaker In a gas, the particles are far apart, so that the particles do not attract each other and can move freely about.

attractive forces: forces between particles which hold the particles in fixed positions in a solid

bonds: another name for the forces between particles

Demonstrating the kinetic model

The kinetic theory can be modelled using small balls or marbles in a tray.

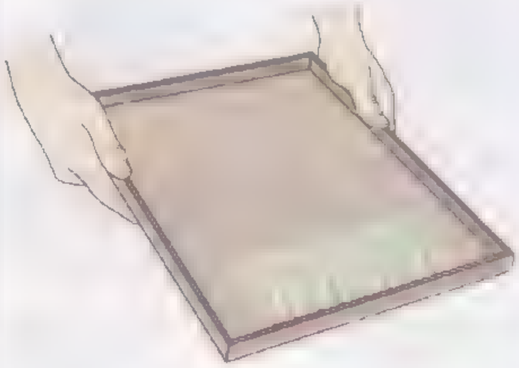


Figure 9.11: Modelling kinetic theory using marbles in a tray.

1. Place some identical small balls or marbles on a shallow tray. They should cover about one-quarter of the area of the tray.
2. Tip the tray slightly so that the balls all roll to the lower end. The pattern they form is like the arrangement of particles in a solid.
3. Keep the tray slightly tipped and shake it gently so that the balls can move about. This is like a liquid.
4. Keep shaking the tray and tip it so that it becomes horizontal. The balls move around freely, colliding with each other and the sides of the tray. This is like the particles in a gas.

CONTINUED

Your task is to make a video, or a presentation to explain the kinetic model, using the tray of balls. You could:

- show the arrangement and movement of particles in each of the three states
- demonstrate absolute zero
- demonstrate and explain changes of state – melting, boiling, condensing and freezing
- model Brownian motion (hint: use a larger, different-coloured ball for the smoke particle)
- add some different-coloured balls to one corner of the tray to represent perfume; show how the perfume diffuses (spreads out)

Questions

4 Sketch three diagrams to show the arrangement of molecules in a solid, a liquid and a gas.

5 a In which state of matter are the particles most closely packed?

b In which state of matter are they most widely separated?

c In which state do the particles move fastest?

6 a Describe what is meant by Brownian motion.

b How can the kinetic model be used to explain Brownian motion?

c A student did an experiment to observe Brownian motion. She then repeated the experiment in a much colder room. Describe and explain how her observations would change.

7 Use the kinetic model of matter to explain why we can walk through air and swim through water but we cannot walk through a solid wall.

9.3 Gases and the kinetic model

The kinetic model can help us understand how gases behave. Thinking about the particles in a gas helps us answer questions about the gas.

Why does a gas cause pressure on the walls of its container? Figure 9.12 shows the particles that make up a gas. The particles of a gas move around inside its container, bumping into the sides. The gas causes pressure on the walls of the container because the gas particles are constantly colliding with the walls.

Figure 9.12: Moving gas particles in a container

What happens to a gas when it is heated? Figure 9.13 shows the same gas at a higher temperature. The higher the temperature of a gas, the faster its particles are moving. The particles will hit the walls more often and with more force. This increases the pressure.

Figure 9.13: Heating the gas in a container

What happens when a gas is compressed (squashed)? Figure 9.14 shows the same gas again. This time the volume of the container has been decreased. The gas has been compressed into a smaller space. The particles don't move as far between collisions, so they collide with the walls more often. Decreasing the volume of a gas increases its pressure.

Figure 9.14: Decreasing the volume of a gas in a container

Figure 9.15: Pumping up tyres means squashing a lot more air particles into a fixed space. This increases the pressure.

The cyclist in Figure 9.15 needs to understand gas pressure. He pumps air into his tyres to make them hard. If the temperature rises, the pressure in his tyres will increase even more. This could burst his tyres.

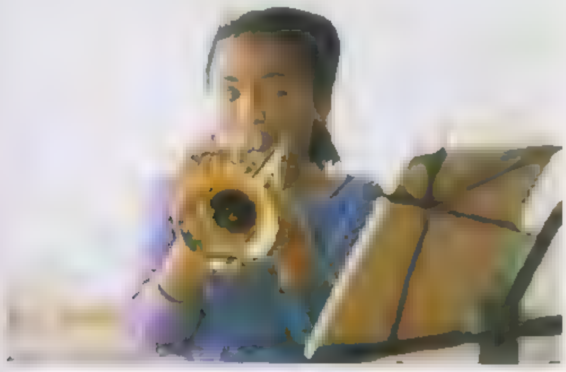


Figure 9.16: You need air pressure to play the trumpet.

To produce a loud sound the girl in Figure 9.16 needs to blow out with as much pressure as she can. Musicians learn to breathe from their diaphragm. Figure 9.17 shows how the girl's diaphragm moves down so a large volume of air can enter her lungs. Her diaphragm then moves up, reducing the volume and so increasing the pressure of the air she blows out and the loudness of her music.

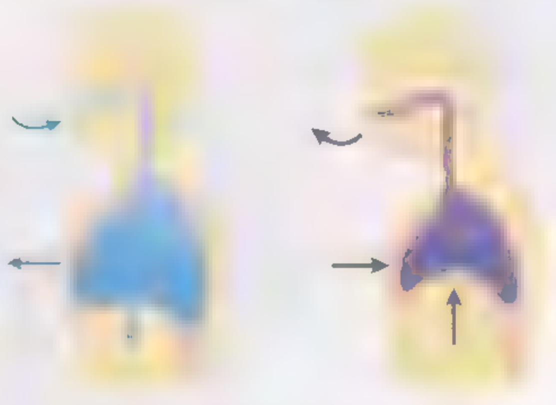


Figure 9.17: The diaphragm moves down as you breathe in and up as you breathe out.

Questions

8 Copy and complete the paragraph.

The molecules in a _____ are constantly moving freely and rapidly and so hit the walls of the container. This creates _______ on the walls. When the gas is heated, the molecules move _______ and the pressure _______. When the gas is compressed, the molecules hit the walls more often and the pressure _______.

9 A balloon is inflated by blowing air into it. Explain what would happen if an inflated balloon was put in a freezer.

10 A tin can containing air is tightly sealed so no air can escape. The can is then heated. Describe what happens to:

- a the speed of the air molecules inside the can
- b how often the air molecules hit the walls of the can
- c the force with which the air molecules hit the walls
- d the pressure on the walls of the can.

9.4 Temperature and the Celsius scale

Temperature is a measure of how hot or cold something is. Temperature is measured using a thermometer. Most thermometers take a minute or so to measure temperature. This is because thermal energy has to be transferred to or from the thermometer until it is at the same temperature as the thing it is measuring.

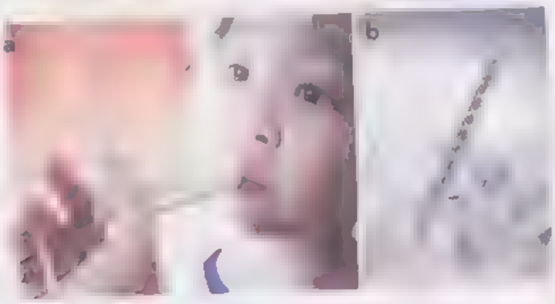


Figure 9.18a: Thermal energy transfers from the girl to the thermometer until they are at the same temperature **b:** Thermal energy transfers from the thermometer to the ice until they are at the same temperature

Temperature and internal energy

A thermometer tells us about the average energy of the particles in the object whose temperature we are measuring. It does this by sharing the energy of the particles. If they are moving rapidly, the thermometer will indicate a higher temperature. Placing a thermometer into an object to measure its temperature is rather like putting your finger into some bath water to detect how hot it is. Your finger does not have a scale from 0 to 100, but it can tell you how hot or cold the water is, from uncomfortably cold to comfortably warm to painfully hot.

The temperature of an object is a measure of the average kinetic energy of its particles. Because it is the average kinetic energy of a particle, it does not depend on the size of the object.

- Internal energy is the total energy of all of the particles.
- Temperature is a measure of the average kinetic energy of the individual particles.

A bath of water at 50 °C can have the same temperature as a cup of tea, but it has more internal energy than the cup of tea because it has far more molecules.

temperature: a measure of how hot or cold something is; a measure of the average energy of the particles in a substance

The temperature of a firework may reach 1500 °C, which means its particles have very high kinetic energy, but it has less total energy than the bath because it has very few particles.

Figure 9.19: The firework has the fastest particles and so the highest temperature. The bath water has many more particles and much more internal energy than the tea

The Celsius temperature scale

The melting and boiling points of water are used to define the Celsius temperature scale.

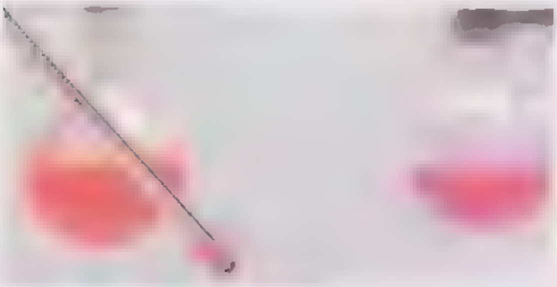


Figure 9.20: A modern liquid-in-glass thermometer.

Thermometers like the one shown in Figure 9.20 are used in school laboratories. The bulb contains a liquid which expands when it gets hot. The liquid moves into the tube and we can read the temperature on the scale.

The liquid used is usually alcohol. This expands a lot when heated and it is safe.

Some thermometers use mercury. Mercury thermometers can be used at very low temperatures. Mercury is poisonous so mercury thermometers are not used in schools.

The scale was devised by the Swedish scientist Anders Celsius.

His scale is known as the Celsius scale. It has two **fixed points**:

- 0 °C: the melting point of pure ice at atmospheric pressure
- 100 °C: the boiling point of pure water at atmospheric pressure.

Each time he made a new thermometer, Celsius would **calibrate** it. He put the thermometer in melting ice and marked 0 °C on the thermometer. He then put it in boiling water and marked 100 °C. He then divided the space between these points into 100 parts. Each part represents one degree Celsius.

The Kelvin temperature scale

Kinetic theory suggests there is a limit to how low temperatures can go. The lowest possible temperature (the point at which molecules have no kinetic energy) is −273 °C. This is called absolute zero.

The **Kelvin temperature scale** starts from absolute zero, or −273 °C. Temperatures measured on this scale are called absolute temperatures. Scientists often measure temperatures using the Kelvin scale. A change in temperature of one degree is the same for both scales. The Kelvin temperature (T) can be calculated from the Celsius temperature (θ) using the equation:

$$T\,(\text{K}) = \theta(°\text{C}) + 273$$

KEY EQUATION

conversion between Kelvin temperature and degrees Celsius:

$$T\,(\text{K}) = \theta(°\text{C}) + 273$$

[illegible]

Calculate the absolute temperature of the human body. Assume that the temperature of the human body is 37 °C

$T\,(\text{K}) = \theta\,(°\text{C}) + 273$

$T = 37 + 273 = 310\,\text{K}$

[illegible]

fixed points: known values used to calibrate a measuring instrument

calibrate: to mark a standard scale on to a measuring instrument

Kelvin temperature scale: (or the absolute temperature scale) the temperature measured from absolute zero. A difference in temperature of 1 kelvin is the same as a difference of 1 °C. 0 K is approximately −273 °C

Questions

11 Copy and complete these sentences.

A thermometer is used to measure ______, which is a measure of how hot something is.

It is measured in ______ or ______.

Temperature depends on how fast the ______ are moving.

12 A laboratory thermometer has no temperature markings. Describe how you could use ice and boiling water to calibrate the thermometer.

13 Calculate the temperature in kelvin of:

- **a** a classroom at 20 °C
- **b** lava at 800 °C
- **c** the surface temperature of minor planet Pluto at −233 °C.

9.5 The gas laws

The temperature, pressure and volume of a gas all affect each other. The gas laws explain mathematically how the three affect each other. There are laws describing how each of these quantities affects the others, but we will look just at the law connecting the pressure of a gas and its volume.

It is important to be clear about what the terms 'temperature', 'pressure' and 'volume' mean. The gas laws all refer to a fixed mass of gas. Imagine the gas in a sealed container which can be squashed or heated. The number of molecules does not change.

The temperature of a gas is a measure of the average kinetic energy of the molecules. In a hot gas, the molecules move faster than in a cold gas.

The pressure of a gas is caused by atoms or molecules hitting the walls, changing momentum and so causing a force. The pressure is the force per unit area on the walls of the container.

Pressure and volume

In 1662, Robert Boyle, a physicist and chemist, investigated the relationship between the pressure on a gas, p, and its volume, V.

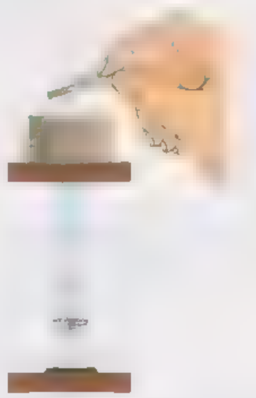


Figure 9.21: Increasing the pressure on a gas decreases its volume.

The effect of increasing the pressure on a gas can be investigated using the simple apparatus shown in Figure 9.21. Adding weights increases the pressure and causes the volume of the gas to decrease.

Figure 9.22 shows a more accurate method. In this apparatus, some air is trapped inside the vertical glass tube. The oil in the bottom of the apparatus can be compressed with a pump, so that it pushes up inside the tube, compressing the air. The [illegible] read from the scale. The pressure exerted on it by the oil can be read from the dial gauge.

Increasing the pressure on the gas decreases its volume. Table 9.3 shows some typical results. Boyle found a mathematical relationship between the pressure, p, and the volume, V, of the gas.

Figure 9.22: Apparatus for increasing the pressure on a gas. A fixed mass of air is trapped inside the tube, and the pressure on it is increased.

Pressure, p/Pa	Volume, V/cm^3	Pressure × volume, pV/Pa cm^3
100	60	6000
125	48	6000
150	40	6000
200	30	6000
250	24	6000
300	20	6000

Table 9.3: Typical results for an experiment into pressure and volume of gas. The temperature of the gas does not change.

Boyle's experiments showed that increasing the pressure decreased the volume. This is shown in Figure 9.23a.

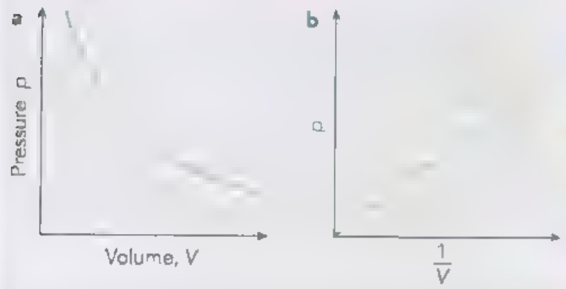


Figure 9.23: Two graphs to represent the results of a Boyle's law experiment. **a**: The graph of pressure against volume shows that increasing the pressure causes a decrease in the volume. **b**: The mathematical relationship between p and $\frac{1}{V}$ can be seen from this graph. It is a straight line through the origin, which means that pressure is inversely proportional to volume.

Boyle also found that when he multiplied pressure by volume, he always got the same result. You can see this in the last column of Table 9.3.

This can be written mathematically as:

pV = constant

relationship between pressure and volume for gas at a constant temperature:

pV = constant

This relationship can be expressed in different ways. We can write the same idea in a way that is useful for doing calculations:

initial pressure × initial volume = final pressure × final volume

Or, $p_1V_1 = p_2V_2$

where p_1 and V_1 are one pair of readings of pressure and volume, and p_2 and V_2 are another pair.

Doubling the pressure halves the volume. This means that pressure is **inversely proportional** to volume. Using the symbol ≠ ('is proportional to'), we can write

$p ≠ \frac{1}{V}$ or $V ≠ \frac{1}{p}$

Figure 9.23b shows that plotting p against $\frac{1}{V}$ gives a straight-line graph passing through the origin.

Finally, we can write the relationship in words, the volume of a fixed mass of gas is inversely proportional to its pressure, provided its temperature remains constant

inversely proportional two quantities are inversely proportional when increasing one quantity decreases the other by the same factor; doubling one quantity halves the other

A scuba diver releases a bubble of air. The bubble has a volume of $2\,cm^3$. He watches it rise to the surface expanding as it rises. The diver is at a depth where the pressure is 5 atmospheres. What will the volume of the bubble be when it reaches the surface, where the volume is 1 atmosphere? Assume that the temperature does not change

Step 1: Write down the initial and final values of the quantities that we know

p_1 = 5 atmospheres

$V_1 = 2\,cm^3$

p_2 = 1 atmosphere

[illegible]

Step 2: Write down the Boyle's law equation and substitute values.

$p_1V_1 = p_2V_2$

5 atmospheres × $2\,cm^3$ = 1 atmosphere × V_2

Step 3: There is only one unknown quantity in this equation (V_2). Rearrange it and solve

$$V_2 = \frac{p_1V_1}{p_2}$$

$$= \frac{5\text{ atmospheres} \times 2\,cm^3}{1\text{ atmosphere}} = 10\,cm^3$$

Answer

The volume of the air increases to $10\,cm^3$

Worked Example 9.2 shows how to use the equation $p_1V_1 = p_2V_2$ to find how the volume of a gas changes when the pressure on it is changed. You can use the same equation to work out how the pressure changes when the volume is changed.

Units

In the equation $p_1V_1 = p_2V_2$, it does not matter what units we use for p and V, as long as we use the same units for both values of p and the same units for both values of V.

The standard unit of pressure is the Pascal (Pa) 1 Pa = 1 N/m^2. Pressure can also be measured in kPa, N/cm^2 or atmospheres. One atmosphere is approximately 100 kPa.

Volume is usually measured in m^3, dm^3, cm^3 or litres.

Questions

14 What do each of the terms in the equation $p_1V_1 = p_2V_2$ represent?

15 The pressure on 6 dm^3 of nitrogen gas is doubled at a fixed temperature. What will its volume become?

16 A flask holds 6 litres of air at a pressure of 2 atmospheres. Calculate the volume when the gas is compressed by increasing the pressure to 6 atmospheres. Assume that the temperature remains constant.

REFLECTION

Physics involves a lot of calculations. Presenting your calculations clearly helps you check your work. It also helps you identify any errors.

Look back over your calculations. Which steps are you using?

- Identify which values are given in the question.
- Check that the units are consistent and change them if necessary.
- Write down the equation.
- Substitute values into the equation.
- Rearrange the equation if needed.
- Calculate the answer.
- Give units for the answer.

Can you make your calculation answers more clear? Make a note of what you could improve and refer to this next time you are doing calculations.

Your task is to make a game to check how well you have understood this topic. You can invent your own game or use one of the ideas below.

Make pairs of cards, one with a key word and the other with its definition. Do this for as many key words or ideas as you can find. Be creative – for example, you could draw Brownian motion rather than write a definition.

Put all the cards face down on a table, making sure they are mixed up.

Players take turns to turn over two cards. If they match, the player keeps them and takes another go. If they don't match, the player turns them face down again and the next player takes a turn.

The winner is the player with most cards at the end.

Banned words

In this game a player takes a card which has a key word on it and a list of banned words.

An example is shown here.

Condensation
• liquid • gas • cool • particle

The player has to describe the word 'condensation' to their team without using any of the banned words. They could say, 'it is the change of state that happens when water vapour turns to water'.

CONTINUED

You can make your game harder or easier by the words you choose for your banned list.

Make a set of cards for the following words and phrases. solid, liquid, gas, vapour, melting, evaporation, condensation, freezing, melting point, boiling point, kinetic model of matter, Brownian motion, temperature, diffuse, expand, change of state, Boyle's law, Pascal.

When you have made your cards, swap with another group and play the game. Players take turns choosing a card and describing the word to their team. The aim is to get through all the cards as quickly as possible.

Matter can exist in three states – solid, liquid and gas.
Solids have a fixed shape and volume. Liquids have a fixed volume but take the shape of their container. Gases expand to fill their container.
The kinetic model explains the behaviour of materials by describing what is happening to the particles of which they are made.
According to the kinetic model, matter is made of moving particles that are close together in solids and liquids, and far apart in gases.
There are attractive forces between particles that act strongly when the particles are close together
In Brownian motion, the movement of water or air particles is revealed by their effect on visible grains of pollen or smoke particles.
As the temperature of a substance increases, the kinetic energy of its particles increases.
The particles of a gas bombard the walls of its container. This causes pressure. Increasing temperature increases pressure. Decreasing the volume increases the pressure.
Temperature can be measured using the Kelvin temperature scale which has its zero at −273 °C.
Pressure and volume are related by the equation pV = constant.

1 Which one of these statements is describing a gas? **[1]**

A It expands to fill the volume of its container.

B It has a fixed size and shape.

C It has a fixed volume but takes up the shape of its container.

D It has strong forces between the particles.

NTINUED

2 Brownian motion can be observed by looking at smoke particles under a microscope. What causes the movement of the smoke particles? [1]

A The smoke particles are moved by air currents.
B The smoke particles hit the walls of the container.
C Air molecules hit the smoke particles.
D There are strong forces between the smoke particles.

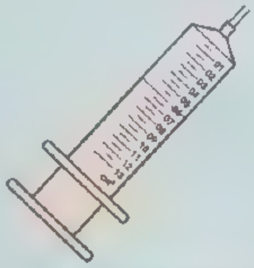
3 Describe the differences between solids, liquids and gases in terms of the arrangement and movement of their particles. [6]

4 A student observes smoke particles under a microscope. The smoke is lit up so she sees the smoke particles as dots of light.

a Describe the movement of the smoke particles. [1]
b Name the particles which are causing this movement. [1]
c Explain why observation of this movement provides evidence for the kinetic model of matter. [2]

[Total: 4]

5 The diagram shows a syringe containing a small amount of air. The end of the syringe is sealed so no air can enter or leave.



a Determine the amount of air in the syringe from the diagram. [1]
b A student pushes in the end of the syringe, compressing the gas. State and explain what happens to the pressure of the air. [2]
c The syringe is placed on a radiator. After a while, the student notices that the volume of the air has increased. Explain in terms of the air molecules why this has happened. [2]

[Total: 5]

[illegible] Before going for a bike ride, a cyclist pumps his tyres up so they have a pressure [illegible] atmospheres. Straight after his ride, the cyclist checks his tyre pressure [illegible] atmospheres. Explain why it has increased. [2]

b After a [illegible] the pressure returns to [illegible] atmospheres. He releases [illegible] drops to [illegible] atmospheres. The tyre has a volume of [illegible] Calculate the volume of air that will be released from the tyre. [4]

[Total: 6]

[illegible]

describe: state the points of a topic; give characteristics and main features

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

determine: establish an answer using the information available

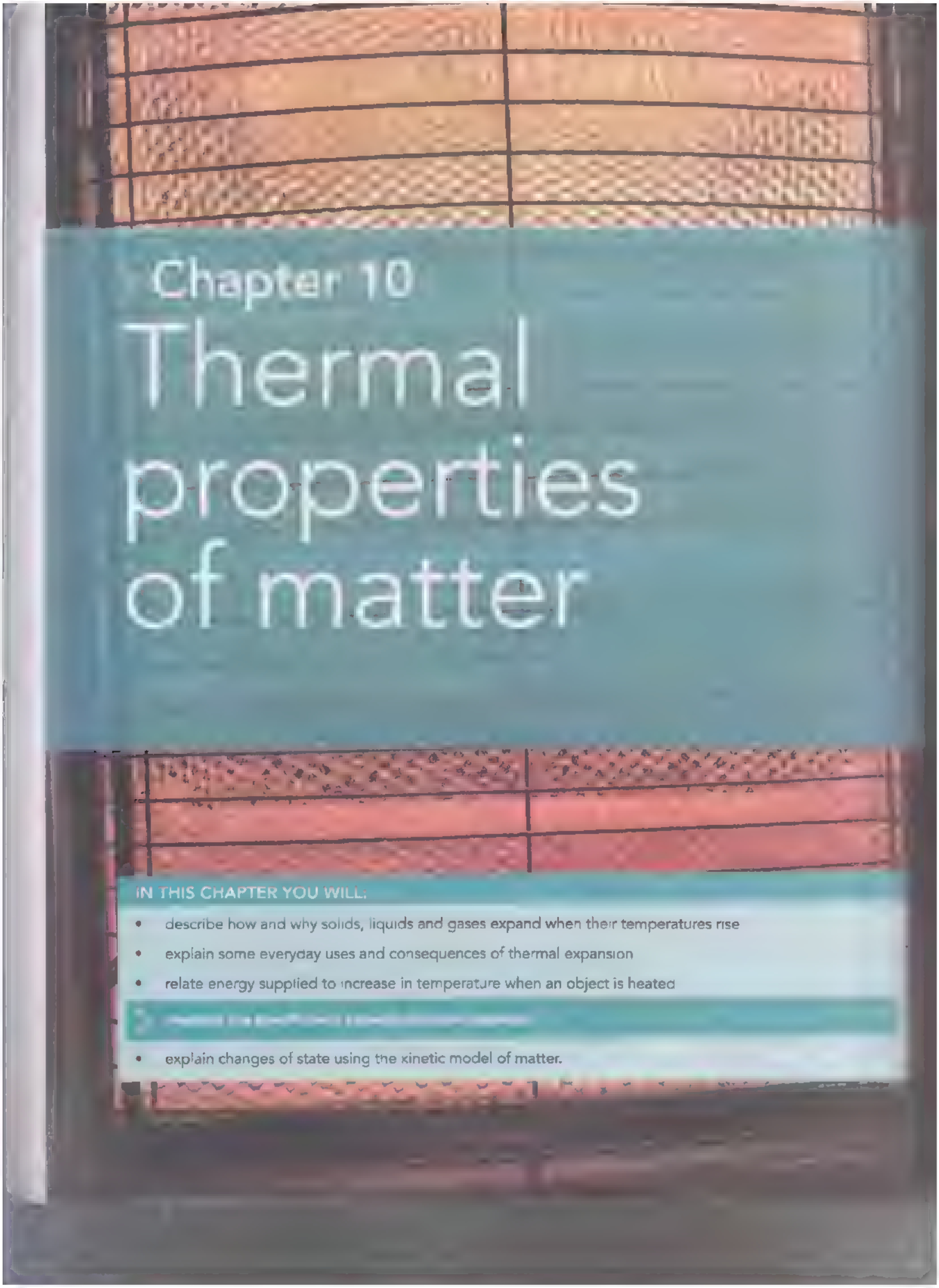
state: express in clear terms

calculate: work out from given facts, figures or information

[illegible]TION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Describe the shape and volume of solids, liquids and gases.	9.1			
Draw and explain particle diagrams showing the separation and arrangement of particles in solids, liquids and gases.	9.2			
Describe the movement of particles in all three states of matter	9.2			
Describe and explain Brownian motion.	9.2			
Use the kinetic model to explain gas pressure.	9.3			
Describe and use the Celsius temperature scale.	9.4			
Describe and use the Kelvin temperature scale	9.4			
Convert temperatures from Celsius to Kelvin and from Kelvin to Celsius.	9.4			
Relate gas pressure to the change in force created per unit area of particles hitting the wall of a container	9.5			
Recall and use the equation pV = constant	9.5			



Chapter 10

Thermal properties of matter

IN THIS CHAPTER YOU WILL:

- describe how and why solids, liquids and gases expand when their temperatures rise
- explain some everyday uses and consequences of thermal expansion
- relate energy supplied to increase in temperature when an object is heated
- explain changes of state using the kinetic model of matter.

GETTING STARTED

Each of these pictures relates to a change of temperature or a change of state

Look at the pictures and discuss them with a partner.

What change is shown?

Describe the physics of what is happening, using as many key words as you can

Why is the chameleon included?

Figure 10.1: Changes involving thermal energy

STRANGE BEHAVIOUR OF WATER

Figure 10.2: The water below the ice is cold, but not cold enough to freeze

Most substances expand when they get hot and contract when they get cold. Water does not always follow this rule. Think about how a pond cools down in cold weather. As the air temperature drops, the water at the top of the pond is cooled by the cold air above it and contracts. This makes the water at the top of the pond more dense, so it sinks to the bottom. The coldest water will be at the bottom of the pond. If this continued, ice would form at the bottom of the pond.

Fortunately for the fish, water does not keep contracting. As it cools from 4 °C to 0 °C, the water expands. This means that the colder water is less dense than the water below it and so it remains at the top. This water continues to cool and eventually freezes. The ice forms at the top of the pond, not the bottom. This means fish can survive in the water beneath the ice. This property of water is called the anomalous expansion of water

Unlike most substances, water is less dense as a solid (ice) than it is as a liquid. This means that ice floats in water. Most substances are more dense when they are solid and so do not float. This strange behaviour is caused by the hydrogen bonds in water which cause it to form a crystal structure with the particles in ice more spaced out than in water.

Discussion questions

1 Sketch a graph to show how the density of water changes from 0 to 10 °C.

2 Discuss what would happen to life on Earth if water froze like other liquids so that ponds froze from the bottom up.

10.1 Thermal expansion

Most substances – solids, liquids and gases – expand when their temperature rises. This is called **thermal expansion**. Thermal expansion happens because the particles gain energy and move faster, pushing each other further apart.

The expansion of solids

Figure 10.3 shows an experiment that demonstrates that a metal ball expands when it is heated.

- When the ball is cold, it just fits through the ring.
- The ball, but not the ring, is heated strongly. It now will not pass through the ring. It has expanded.
- When the ball cools down, it contracts and returns to its original size and will once again pass through the ring.

Figure 10.3a: The metal ball is cold and has passed through the ring. **b:** The metal ball is hot. It has expanded and will no longer fit through the ring.

thermal expansion: the increase in volume of a material when its temperature rises

Uses of expansion

Rivets are used in shipbuilding and other industries to join metal plates. A red-hot rivet is passed through holes in two metal plates and then hammered until the ends are rounded (Figure 10.4). As the rivet cools, it contracts and pulls the two plates together tightly.

A metal lid or cap may stick on a glass jar or bottle, and be hard to unscrew. Heating the lid (for example, by running hot water over it) causes it to expand. The glass expands much less than the metal lid, meaning that the lid loosens and can be removed.

Figure 10.4: Joining two metal plates using a rivet

Figure 10.5: Steel tyres are heated so they expand and can be fitted to train wheels. They contract and fit very tightly.

A steel 'tyre' can be fitted on to the wheel of a train while the tyre is very hot. It then cools and contracts, so that it fits tightly on to the wheel.

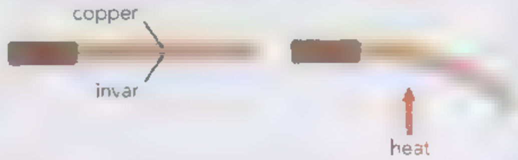


Figure 10.6: A bimetallic strip. Invar is a metal alloy which expands very little when heated. Copper expands more. This difference in expansion causes the strip to bend.

A bimetallic strip (Figure 10.6) is designed to bend as it gets hot. The strip is made of two metals joined firmly together. One metal expands much more than the other.

As the strip is heated, this metal expands, causing the strip to bend. The metal that expands more is on the outside of the curve, because the outer curve is longer than the inner one. These strips are used in devices such as fire alarms and thermostats. Thermostats are used to control the temperature of devices such as ovens and irons.

ACTIVITY 10.[illegible]

Uses of a bimetallic strip

A bimetallic strip can be used in an electric circuit to complete or break a circuit depending on the temperature.

- Design a fire alarm circuit which will sound a buzzer when it gets hot. Design a poster to promote your invention. Include a circuit diagram and an explanation of how the device works
- Consider how you could change your circuit to make an alarm to warn gardeners when temperatures are dropping and allow them to protect delicate plants from frost. Design a poster for a frost alarm.

Consequences of expansion

The expansion of materials can cause problems. For example, metal bridges and railway lines expand on hot days, and there is a danger that they might bend. To avoid this, bridges are made in sections, with expansion joints between the sections (Figure 10.7). On a hot day, the bridge expands and the gaps between sections decrease. Railway lines are now usually made from a metal alloy that expands very little. On a concrete roadway, you may notice that the road surface is in short sections. The gaps between are filled with soft tar, which becomes squashed as the road expands.

Figure 10.7: This lorry is about to cross an expansion joint on a road bridge. On a hot day, the bridge expands and the interlocking teeth of the joint move closer together

The expansion of liquids

Many thermometers use the expansion of a liquid to measure temperature. As the temperature of the liquid rises, it expands and the level of liquid in the tube rises.

Figure 10.8: As the temperature drops, so does the volume of the liquid in the thermometer. The alcohol in this thermometer remains liquid at very low temperatures

Glass containers may crack when hot liquid is placed in them. This is because the inner surface of the glass expands rapidly, before the thermal energy has passed through to the outer surface. The force of expansion cracks the glass. To avoid this, glass such as Pyrex has been developed that expands very little on heating. An alternative is toughened glass, which has been treated with chemicals to reduce the chance of cracking

The expansion of gases

Gases expand when they are heated, just like solids and liquids. We can explain this using the kinetic model of matter (see Chapter 9). Figure 10.9 shows some gas in a cylinder fitted with a piston. At first, the gas is cold and its particles press weakly on the piston. When the gas is heated, its particles move faster. Now they push with greater force on the piston and push it upwards. The gas has expanded.

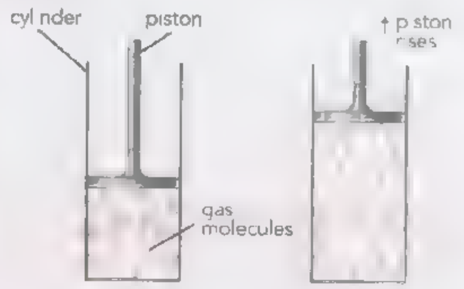


Figure 10.9: A gas expands when it is heated at constant pressure

The expansion of gases as they heat up means that the density of a hot gas is lower than the density of the same gas when it is cold. This is why hot air rises (you will learn more about this in Chapter 11).

Figure 10.10: The expansion of air as it heats up creates thermal currents, which this hang glider is using

Comparing solids, liquids and gases

Which expands most, a solid, a liquid or a gas, for a given rise in temperature?

- Solids expand least when they are heated. Some, such as Pyrex glass and invar metal alloy, have been designed to expand as little as possible.
- Liquids generally expand more than solids.
- Gases expand even more than liquids.

There are some exceptions to this. For example, liquid paraffin expands very rapidly on heating. Petrol (gasoline) is stored in cool underground tanks. If a motorist fills their tank on a hot day, the petrol will heat up and expand. This can cause the fuel to overflow when it expands.

When a material expands, its particles (atoms or molecules) do not get any bigger. However, they have more energy, so they can move around more and take up more space. It is difficult for the particles of a solid to push their neighbours aside, so a solid does not expand much. When a gas is heated, its particles move about more rapidly, and it is easy for them to push the walls of their container further apart, so that the gas takes up more space.

Questions

1 Copy and complete these sentences:

When an object is heated it ______. When it cools it ______.

Liquids expand more than ______ but less than ______.

A bimetallic strip is made of two ______ which expand by different amounts when heated. This causes the strip to ______.

2 Look at the bridge in Figure 10.11. One end of the bridge is on rollers rather than being fixed. Explain how this helps it cope with extreme temperatures.

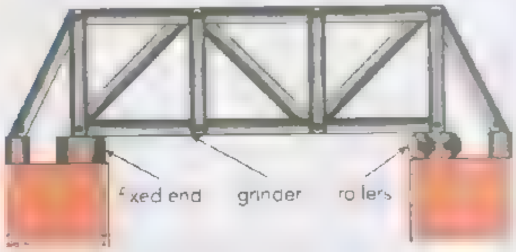


Figure 10.11: A bridge.

3 Alcohol has a freezing point of −115 °C. Explain why coloured water could not be used in the thermometer in Figure 10.8.

4 Figure 10.12 shows an experiment to compare the expansion of liquids. Equal volumes of ethanol, water and mercury were heated in a water bath.

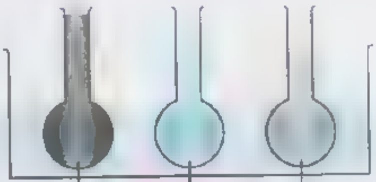


Figure 10.12: Experiment to compare expansion of liquids.

a Which liquid expands the most?

b Explain why this liquid is used in most school laboratory thermometers.

10.2 Specific heat capacity

Energy and temperature

All objects store energy, called internal energy. Internal energy is a measure of the total energy of all the particles in the object. This includes both the kinetic energy of the particles and chemical potential energy of the bonds between them. Supplying thermal energy to an object will raise its temperature. The particles will move faster as they gain kinetic energy

However, energy and temperature are not the same thing. The internal energy of an object is the total energy of all its particles. A cup of tea may have a higher temperature than a bath of warm water, but the energy stored in the bath water is much greater as there are many more water particles.

Figure 10.13: The tea is hotter than the bath so its particles move faster. However, the bath has far more particles and stores more energy

Heating water causes the water particles to gain kinetic energy and speed up. It takes more energy to raise the temperature of a large amount of water because more particles need to have their speed changed. This section deals with increasing the kinetic energy of particles. We will look at the potential energy in Section 10.3

Suppose that you want to make a hot drink for yourself and some friends. You need to boil some water You will be wasting energy if you put too much water in the kettle or pan. It is sensible to boil just the right amount Also, if the water from your tap is really cold, it will take longer, and require more energy, to reach boiling point.

So, the amount of energy you need to supply to boil the water will depend on two facts

- the mass of the water
- the increase in temperature.

In order to calculate how much energy must be supplied to boil a certain mass of water, we need to know a third fact:

- it takes 4200 J to raise the temperature of 1 kg of water by 1 °C.

Let us assume that the cold water from your tap is at 20 °C You have to provide enough energy to heat it to 100 °C, so its temperature must increase by 80 °C. Let us also assume that you need 2 kg of water for all the drinks

The amount of energy required to heat 2 kg of water by 80 °C is, therefore.

$$\text{energy required} = 2\,\text{kg} \times 4200\,\text{J/(kg °C)} \times 80\,\text{°C}$$
$$= 672\,000\,\text{J} = 672\,\text{kJ}$$

Another way to express the third fact above is to say that the specific heat capacity of water is 4200 J per kg per °C or 4200 J/(kg °C). In general, the **specific heat capacity** of a substance is defined as the energy needed to raise the temperature of 1 kg of the substance by 1 °C. It is defined by the equation:

$$c = \frac{\Delta E}{m\Delta\theta}$$

$$\text{specific heat capacity} = \frac{\text{energy required}}{\text{mass} \times \text{temperature increase}}$$

$$c = \frac{\Delta E}{m\Delta\theta}$$

where c = specific heat capacity, ΔE = energy required, m = mass and $\Delta\theta$ = increase in temperature. Δ is the Greek letter delta; it means 'change in'.

The energy needed can be calculated by rearranging the equation:

energy required = mass × specific heat capacity × increase in temperature

$$\Delta E = mc\Delta\theta$$

specific heat capacity: the energy required per unit mass per unit temperature increase

Worked Example 10.1 shows how to use this equation in more detail.

A kettle heats 1.5 kg of water. How much energy is needed to raise the temperature of the water from 20 °C to 100 °C? Assume that specific heat capacity of water = 4200 J/(kg °C).

Step 1: Calculate the required increase in temperature.

increase in temperature = 100 °C − 20 °C
= 80 °C

Step 2: Write down the other quantities needed to calculate the energy.

mass of water = 1.5 kg

specific heat capacity of water
= 4200 J/(kg °C)

Step 3: Write down the equation for energy required, substitute values, and calculate the result.

energy required = mass × specific heat capacity × increase in temperature

= 1.5 kg × 4200 J/(kg °C) × 80 °C

= 504 000 J

= 504 kJ

Answer

504 kJ of energy is required to boil the water.

The meaning of specific heat capacity

Energy is needed to raise the temperature of any material. The energy is needed to increase the kinetic energy of the particles of the material. In solids, they vibrate more. In gases, they move about faster. In liquids, it is a bit of both.

We can compare different materials by considering standard amounts (1 kg), and a standard increase in temperature (1 °C). Different materials require different amounts of energy to raise the temperature of 1 kg by 1 °C. In other words, they have different specific heat capacities. Table 10.1 shows the values of specific heat capacity for a variety of materials.

Table 10.1 shows that there is quite a wide range of values. The specific heat capacity of steel, for example, is one-tenth that of water. This means that, when you supply equal amounts of energy to 1 kg of steel and to 1 kg of water, the temperature of the steel rises ten times as much as the temperature of the water.

Type of material	Material	Specific heat capacity / J/(kg °C)
metals	steel	420
	aluminium	910
	copper	385
	gold	300
	lead	130
non-metals	glass	670
	nylon	1700
	polythene	2300
	ice	2100
liquids	water	4200
	sea water	3900
	ethanol	2500
	olive oil	1970
gases	air	1000
	water vapour	2020 (at 100 °C)
	methane	2200

Table 10.1: Specific heat capacities of a variety of materials.

The specific heat capacity of water

Water is an unusual substance. As you can see from Table 10.1, it has a high value of specific heat capacity (s.h.c.) compared with other materials. This has important consequences:

- it takes a lot of energy to heat up water
- hot water takes a long time to cool down.

The consequences of this can be seen in our climates. In the hot months of summer, the land warms up quickly (low specific heat capacity) while the sea warms up more slowly. In the winter, the sea cools gradually while the land cools rapidly. People who live a long way from the sea (in the continental interior of North America or

Eurasia, for example) experience freezing winters and very hot summers. People who live on islands and in coastal areas (such as western Europe) are protected from climatic extremes because the sea acts as a store of heat in the winter, and stays relatively cool in the summer.

EXPERIMENTAL SKILLS 10.1

Measuring the specific heat capacity of a metal

In this experiment you will heat a metal block. You will measure the energy you supply, the mass of the metal and the change in temperature. You will then be able to calculate the s.h.c. of the metal.

You will need:

- a block of metal with holes for the thermometer and heater
- insulation for the block
- electric heater
- power pack
- joulemeter (your teacher may show you an alternative way to find the energy used)
- thermometer
- access to balance.

Safety: The electric heater can become extremely hot. Leave it to cool inside the block when you have finished your experiment.

Getting started

1 Should you insulate the metal block? Explain your answer.

2 Why should you measure the mass of the block at the start of the experiment rather than the end?

Method

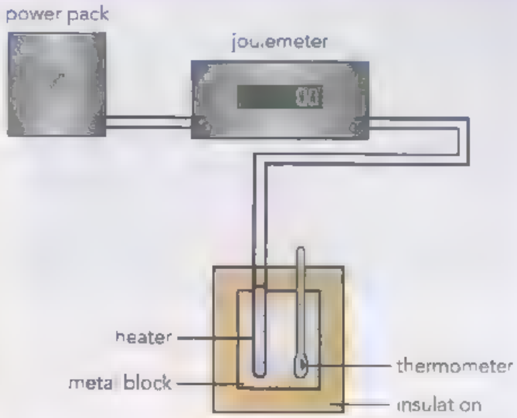


Figure 10.14

1 Measure and record the mass, m, of the block in kg.

2 Set up the experiment as shown in Figure 10.14.

3 Measure and record the initial temperature (θ_1) of the block.

4 Turn on the power supply.

5 When there has been a temperature rise of 10 °C, turn off the power supply and record the Joulemeter reading.

6 Watch the thermometer for a few minutes and record the highest temperature (θ_2) it reaches.

7 Calculate the change in temperature using $\Delta\theta = \theta_2 - \theta_1$.

8 Calculate the specific heat capacity of the metal using the equation.

$$c = \frac{\Delta E}{m\Delta\theta}$$

EXPERIMENTAL SKILLS 10.2

Measuring the specific heat capacity of water

In this experiment you will heat a mass of water and find its specific heat capacity

You will need:

- a beaker of water with a lid with holes for the thermometer and heater
- insulation for the beaker
- electric heater
- power pack
- joulemeter (your teacher may show you an alternative way to find the energy used)
- thermometer
- access to balance

Safety: The heater and water will get hot. Allow them to cool before clearing away your apparatus

Getting started

1 Why is it important to have a lid on the beaker?

2 How will you measure the mass of the water?

Method

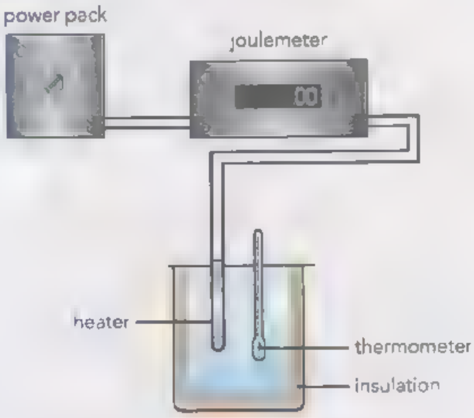


Figure 10.15

1 Put 0.25 kg of water into the beaker.

2 Set up the experiment as shown in Figure 10.15.

3 Measure and record the initial temperature (θ_1) of the block.

4 Turn on the power supply and leave until the temperature changes by about 50 °C.

5 Turn off the power supply. Record the final temperature (θ_2).

6 Calculate the change in temperature using $\Delta\theta = \theta_2 - \theta_1$.

7 Record the joulemeter reading.

8 Calculate the specific heat capacity of the metal using the equation:

$$c = \frac{\Delta E}{m\Delta\theta}$$

Questions

1 Compare your answers with the values of specific heat capacity given in Table 10.1. Are they higher or lower?

2 The thermal energy supplied by the heater heats the heater itself, the thermometer and the surrounding air as well as the block. Explain what effect this will have on the accuracy of your answer.

Questions

5 Table 10 2 gives the specific heat capacities of some materials.

Material	Specific heat capacity
water	4200
go d	300
glass	840
air	1000

Table 10 2

a Name the substance that requires the least amount of energy to raise its temperature

b The table does not give units. What is the unit for specific heat capacity?

c State the amount of energy needed to heat 1 kg of glass by 1 °C

d Calculate the energy needed to heat 1 kg of glass by 10 °C

6 The specific heat capacity of copper is 385 J/kg °C Calculate the energy needed to heat 3 kg of copper

a by 1 °C

b from 20 °C to 50 °C

7 A cook heats 500 g of olive oil in a steel pan which has a mass of 300 g. The oil needs to be heated from 20 °C to 190 °C. Using data from Table 10.1, calculate the thermal energy needed

a to heat the pan

b to heat the oil

c in total

8 The electric kettle in Figure 10 16 has a power rating of 2000 W. It takes 90 seconds to heat 500 g water from 20 °C to boiling

Figure 10 16: An electr c kettle

a Use this information to calculate an approximate value for the specific heat capacity of water

b Compare your answer to the specific heat capacity of water given in Table 10 1 Com on why it is different

10.3 Changing state

Figure 10 17 shows what happens to the temperature when you take some ice from the freezer and heat it at a steady rate. In a freezer, ice is at a temperature well below its freezing point, maybe as low as −20 °C. From the graph, you can see that the ice warms up to 0 °C, then stays at this temperature while it melts. As lumps of ice float in water, both are at 0 °C. When all of the ice has melted, the water's temperature starts to rise again. At 100 °C, the boiling point of water, the temperature again remains steady. The water is boiling to form steam. Eventually, all of the water has turned to steam. If you continue to heat the steam, the temperature of the steam will rise again.

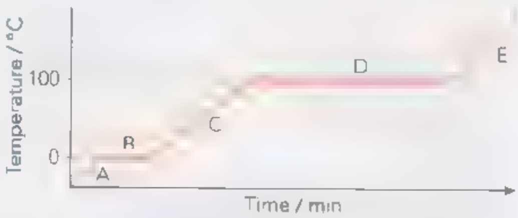


Figure 10.17: A temperature against time graph to show the changes that occur when ice is heated until t eventua ly becomes steam. A. ice is heating up. B: ice is melting C. water is heating up. D: water is boil.ng E: steam is heat ng up

It takes energy to change a solid into a liquid. The temperature stays the same as the ice melts. Similarly, when a liquid becomes a gas, its temperature stays the same even though energy is being supplied to it. This is due to changes in the chemical potential energy in the bonds between the molecules or atoms. Energy must be provided to break bonds and change a substance from solid to liquid. Energy is also needed to overcome the attraction between the particles when a substance changes from liquid to gas. When these changes are reversed, energy is given out.

Condensation is when a gas changes to a liquid. The particles slow down and the particles are drawn together. Solidification, or freezing, is when a liquid changes to a solid. As a liquid loses energy, its particles slow down and the bonds holding the particles together re-form.

The boiling and melting points of a substance change if the air pressure changes. Water has a melting point of 0 °C and a boiling point of 100 °C at standard atmospheric pressure. This is the pressure at sea level which is about 101.32 kPa or 1 atmosphere. At altitude, water boils at a lower temperature.

Figure 10.18: On top of Mount Everest water boils at 71 °C

Investigating a change of state

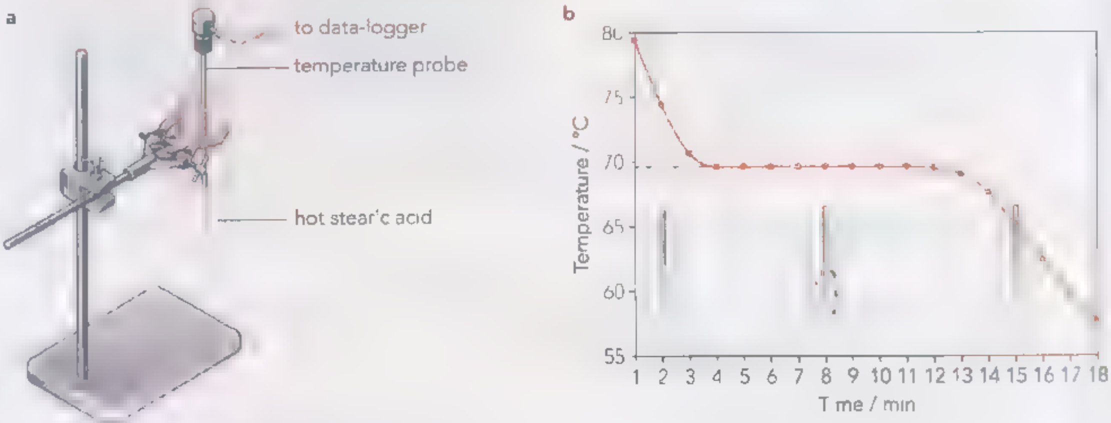


Figure 10.19a: The thermometer measures the temperature of the wax as it cools. **b:** The graph shows how the temperature changes.

Figure 10.19a shows one way to investigate the behaviour of a liquid material as it solidifies. The test tube contains a waxy substance called stearic acid. This is warmed up, and it becomes a clear, colourless liquid. It is then left to cool down, and its temperature is monitored using a thermometer (or an electronic temperature probe) and recorded.

Figure 10.19b shows the results.

At first, the liquid wax cools down. Its temperature drops gradually. The wax is hotter than its surroundings, so thermal energy is transferred to the surroundings. The graph is slightly curved. As the temperature drops, there is less difference between the temperature of the wax and its surroundings, so it cools more slowly.

Now the temperature of the wax stays the same for a few minutes. The tube contains a mixture of clear liquid and white solid. The wax is solidifying. The wax is still transferring thermal energy to the surroundings, because it is still warmer than its surroundings, but its temperature does not decrease.

The wax's temperature starts to drop again. All the wax is now solid. It continues cooling until it reaches the temperature of its surroundings.

The dashed line on the graph has been drawn to find the temperature at which the stearic acid changes from a liquid to a solid.

melting point: the temperature at which a solid melts to become a liquid

boiling point: the temperature at which a liquid changes to a gas (at constant pressure)

The stearic acid experiment (Figure 10.19) shows that a pure substance changes from solid to liquid at a fixed temperature, known as the melting point. Similarly, a liquid changes to a gas at a fixed temperature, known as its boiling point. Table 10.3 shows the melting and boiling points of some pure substances.

Substance	Melting point / °C	Boiling point / °C
helium	272	269
oxygen	−218	183
nitrogen	191	−177
mercury	39	257
water	0	100
iron	2080	3570

Table 10.3: The melting and boiling points of some pure substances. Mercury is interesting because it is the only metal that is not solid at room temperature. Tungsten is a metal, and it has the highest boiling point of any substance. Helium has the lowest melting and boiling points of any element. In fact, helium will only solidify if it is compressed (squashed) as well as cooled.

A pure substance has a clear melting point and a clear and boiling point. A mixture of substances may melt or boil over a range of temperatures. Candle wax is an example. It is not a single, pure substance, and some of the substances in it melt at lower temperatures than others.

Dissolving things in water changes the boiling point and freezing point of the water. For example, salty water boils at a higher temperature than pure water and freezes at a lower temperature.

Not all substances melt or boil when they are heated. Some burn, and others decompose (break down) into simpler substances before they have a chance to change state.

Breaking free

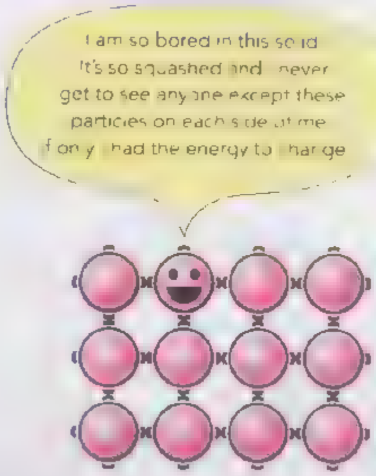


Figure 10.20

Create a comic strip to tell the story of what happens to the particle when it gets what it wants (energy) and changes from a solid to a liquid and then to a gas.

Your comic strip should be:

- engaging (use pictures, colour and humour)
- scientifically correct (check back through the chapter so far; use the correct scientific words and explain what is happening).

PEER ASSESSMENT

Swap comic strips with another group. Study their work and give them feedback. Include:

- three ways it works well
- one suggestion for how it could be even better; this could be something they need to make clearer, or something they could add.

Questions

9 Look at Figure 10.17. Sketch the graph and add notes explaining what is happening during each section.

10 Use Figure 10.19b to determine the melting point of stearic acid.

11 Use the information in Table 9.2 to explain why air doesn't have a fixed melting or boiling point (Hint: air is roughly 80% nitrogen and 20% oxygen)

Evaporation

Figure 10.21: In warm weather puddles evaporate quickly

A liquid can change state without boiling. After it rains, the puddles dry up even though the temperature is much lower than 100 °C. The water from the puddles has evaporated. The liquid water has become a gas called water vapour in the air. This is the process of evaporation. We can think of a vapour as a gas at a temperature below its boiling point.

A liquid evaporates more quickly as its temperature approaches its boiling point. That is why puddles disappear faster on a hot day than a cold day.

Figure 10.22: Fast-moving particles leave the surface of a liquid. This is how the liquid evaporates.

How can we use the kinetic molecular model of matter to explain evaporation? Imagine a beaker of water. The water will gradually evaporate. Figure 10.22 shows the particles that make up the water. The particles of the water are moving around, and some are moving faster than others. Some may be moving fast enough to escape from the surface of the water. They become particles of water vapour in the air. In this way, all of the water particles may eventually escape from the beaker, and the water will have evaporated.

If the temperature of the liquid is higher, more of its particles will have enough energy to escape. This means the liquid will evaporate more quickly. The hottest particles are most likely to escape as they have most energy. When they escape, the average energy of the remaining particles is less, so the liquid cools down.

Cooling by evaporation

If you get wet, perhaps in the rain or after swimming, you will notice that you can quickly get cold. The water on your body is evaporating, and this cools you down. Why does evaporation make things cooler?

Look again at Figure 10.22. The particles that are escaping from the water are the fastest-moving ones. They are the particles with the most kinetic energy. This means that the particles that remain are those with less energy. Now the particles of the liquid have less energy (on average) and so the temperature of the water decreases. The water cools down.

Comparing evaporation and boiling

Evaporation and boiling both involve a liquid tu[rning] into a gas. Evaporation is different from boiling:

- Boiling only happens at the boiling point of th[e] substance. Evaporation occurs at all temperatu[res].
- For a liquid to boil, it has to be heated [...] kinetic energy of its particles must be increased. Evaporation happens when the most energetic particles escape, so evaporation takes energy from the substance.
- Boiling happens throughout the liquid. E[...] only happens at the surface.
- A boiling liquid bubbles. A liquid can evaporate without bubbles.

Speeding up evaporation

We can use the kinetic model to explain some ways of speeding up evaporation.

Increasing the temperature

Figure 10.23: Increasing the temperature increases the rate of evaporation.

Increasing the temperature of the liquid means the particles on average have more kinetic energy. More of the particles will have enough energy to escape. This means the liquid will evaporate more quickly.

Increasing the surface area

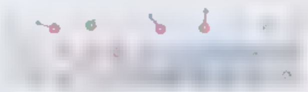


Figure 10.24: Increasing the surface area increases the rate of evaporation.

In Figure 10.24, the liquid has a greater surface area: more of the particles are close to the surface, and so they can escape more easily. This means the liquid evaporates more quickly.

Blowing air across the surface

Figure 10.25: A draught blowing across the surface increases the rate of evaporation.

A draught is moving air. When particles escape from the water, they are blown away so that they cannot fall back into the water. This helps the liquid evaporate quickly.

As a liquid evaporates, the remaining liquid cools. This means that thermal energy will flow to the liquid from any objects in contact with it. When we get hot we sweat. The sweat evaporates, causing thermal energy to flow from the skin. This helps us cool down.

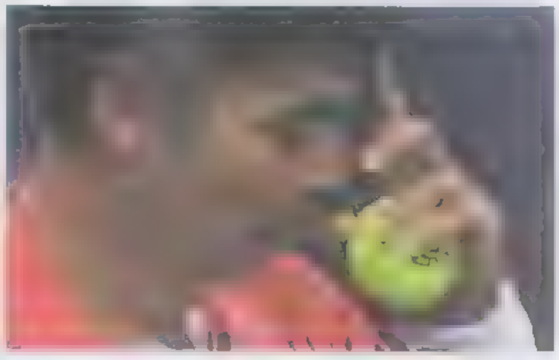


Figure 10.26: Sweating helps us regulate our body temperature in hot conditions.

Fridges use the cooling effect of evaporation (see Figure 10.27). A liquid is compressed then squirted through a narrow hole so its pressure is reduced and it evaporates. This draws thermal energy from inside the fridge into the liquid. The liquid is then pumped out of the fridge to the pipes on the back of the fridge where it is compressed and condenses, releasing the thermal energy to the surroundings.

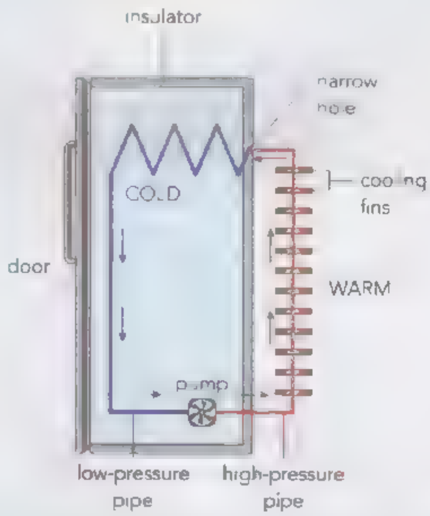


Figure 10.27: The refrigerant liquid absorbs thermal energy from the fridge as it evaporates.

Questions

12 Copy and complete the following sentences.

a ______ is the change from a liquid to a gas at a temperature below the boiling point

b Evaporation causes a liquid to cool because the ______ moving, hotter particles are the most likely to escape. This means the particles left behind are the slower moving, ______ ones

13 Explain in terms of movement and position of particles what happens to an ice cube as it is heated and melts.

14 Tungsten melts at a much higher temperature than iron. What can you say about the forces between the tungsten atoms, compared to the forces between the iron atoms?

15 A solid material is heated but its temperature not rise

a What is happening to the solid

b What happens to the energy that is bein supplied to the material

16 Use the kinetic theory to explain why a wet towe will dry much faster if hung outside on a warm windy day than if left folded up in a bag

17 Explain how covering a bottle of milk with cloth will help to cool the milk

Hot stuff

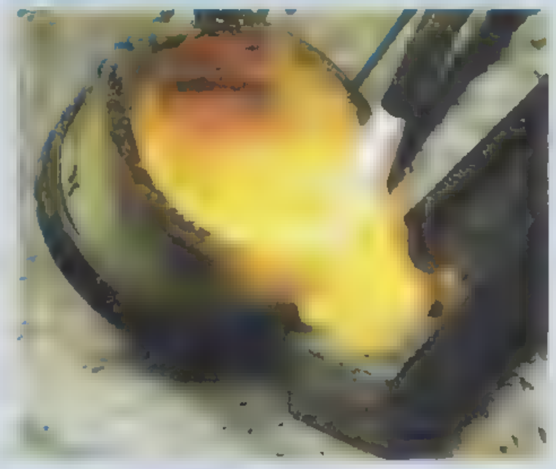


Figure 10.28: Heating gold causes it to melt. Liquid gold can be poured into moulds, where it will cool and solidify.

Option 1: Changing state

Create a video or article for a revision guide to explain changes of state. Show objects changing state, such as an ice cube melting or a puddle of water evaporating (you could use time lapse photography). You should show what is happening to the particles. You may want to use marbles or drawings to represent the particles. You must include the following key words:

- melting
- boiling
- condensing
- solidifying
- internal energy
- temperature.

Write three multiple choice questions for the students to test their understanding to go with your video.

Option 2: Specific heat capacity questions

Specific heat capacity is important in engineering and in the choice of material for different products. Investigate the applications of specific heat capacity in answering questions such as.

- Which is the best metal for a pan?
- What makes a good coolant for the cooling system for an engine?
- Why do the different specific heat capacities of sand and water create sea breezes?
- Which types of food store most thermal energy and so stay hot the longest?

Research one or more of these questions. Present your results as a website entry for a site which answers scientific questions posed by science students. Write a question to test the students understanding. Include a calculation and answer.

CONTINUED

2 Which statement about the difference between evaporation and boiling is true? [1]

A Evaporation happens at any temperature.

B Evaporation happens throughout a liquid.

B Evaporation happens at a specific temperature.

C Evaporation and boiling are not different.

3 What is thermal expansion? [1]

A An increase in density due to an increase in temperature.

B A decrease in density due to a decrease in temperature.

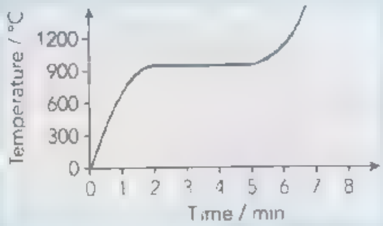
C A decrease in density due to an increase in temperature.

D A decrease in volume due to an increase in temperature.

4 A jeweller is making a silver ring. She heats the silver until it melts, and then continues to heat it for another minute after it has melted. She then pours the molten (melted) silver into a mould and leaves it to cool down.

a Describe what happens to the arrangement and movement of the silver atoms as the silver is heated from room temperature and poured into the mould. [3]

b The graph shows how the temperature of the silver varies as it is heated.

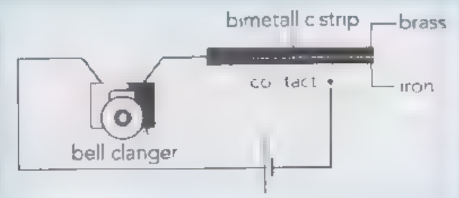


Use the graph to find the melting point of silver. [1]

c State how long it takes for the silver to melt. [1]

[Total: 5]

5 The diagram shows the circuit for a fire alarm using a bimetallic strip.



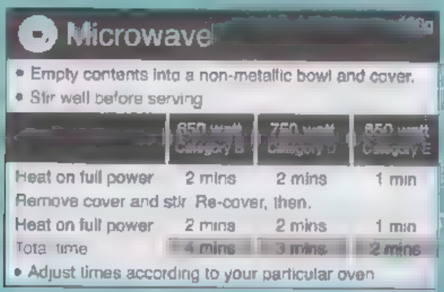
a Brass expands more than iron. Which metal should be at the top of the strip? [1]

b Describe what happens as the temperature rises in case of a fire. [3]

[Total: 4]

describe: state the points of a topic, give characteristics and main features

state: express in clear terms



produce an answer from a given source or recall / memory

calculate work out from given facts, figures or information

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See Topic...	Needs more work	Almost there	Confident to move on
Describe everyday examples of thermal expansion	10.1			
State which expands most, solid, liquid or gas, and explain this in terms of the particles.	10.1			
State the effect of raising an objects, temperature on its internal energy	10.2			
Recall and use the equation $c = \frac{\Delta E}{m\Delta\theta}$.	10.2			
Describe experiments to measure the specific heat capacity of solids and liquids.	10.2			
Describe changes of state as a change in internal energy without a change in temperature.	10.3			
Know why evaporation causes cooling.	10.3			
Explain the factors that increase the rate of evaporation.	10.3			
Explain how an evaporating liquid causes objects in contact with it to cool.	10.3			

> Chapter 11

Thermal energy transfers

IN THIS CHAPTER YOU WILL

- carry out experiments to demonstrate conduction, convection and radiation
- [illegible]
- describe and explain convection currents
- explain thermal energy radiation
- [illegible]
- research applications and consequences of thermal energy transfer

[illegible]

Figure 11.1 shows items that are used to transfer thermal energy or prevent thermal energy transfer. Work in a group to decide what each item is for and how it works. Your teacher will stop you and pick a member of the group to report back on one of the photos. If they can do this they score a point for the team. If they use any of the following terms correctly, your teacher will award bonus points.

conduction	convection	radiation	conductor	insulator	convection current	infrared radiation

Rules.

- All members of the group need to be able to answer.
- You cannot write down your ideas.
- You can write a maximum of three words for each picture as a prompt.

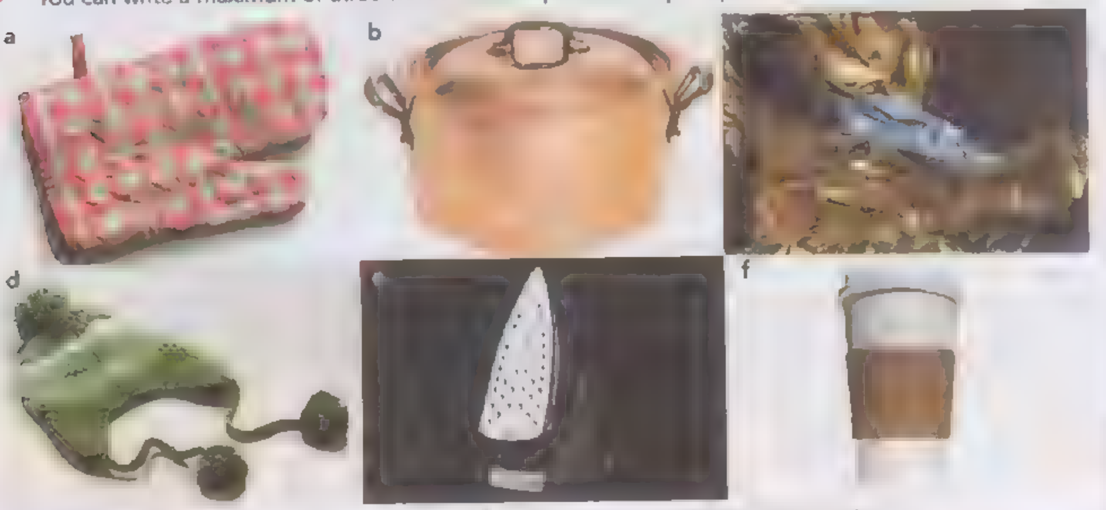


Figure 11.1: A selection of items that transfer thermal energy, or prevent thermal energy transfer

[illegible] LEARN FROM A REINDEER'S NOSE?

Figure 11.2: Reindeer are superbly adapted to prevent thermal energy losses

Reindeer live in some of the most difficult conditions on the planet. They need to cope with temperatures dropping to −50 °C and below.

Reindeer are adapted so they lose very little thermal energy from their bodies. They have two layers of fur: soft fur near the body, then a layer of guard hairs which are hollow tubes containing air. Air is an excellent insulator. The hairs are densely packed, insulating the body so well reindeer can sleep on snow without melting it.

The reindeer's nasal passages serve as a complex thermal energy exchange system. They have a complex system of tubes which allow warm air being breathed out to pass over cold air being breathed in. Thermal energy is transferred to the incoming air so that the air leaving a reindeer's body is cold, and the reindeer keeps the thermal energy. The warm air is cooled by about 21 °C before leaving the reindeer's nose

The reindeer are so well insulated that they are in danger of overheating when running from predators such as wolves.

They lose thermal energy from their large tongues. Also they circulate more blood to their legs, which are less insulated so can give out the thermal energy

It is important that a reindeer does not lose feeling in its nose while finding food in the snow. To keep the nose warm and sensitive, it has extra blood vessels. This means that when a reindeer is photographed with a temperature-sensitive camera, the nose seems to glow.

Figure 11.3: A reindeer's nose has a complex thermal exchange system. Reindeer lose thermal energy through their large tongues

Reindeer have other adaptations that make them suited to life in the Arctic. They need to stick together in blizzards, because they cannot see each other. Their feet make a clicking sound as tendons move across bones. This means they can hear each other. They also have a gland in the leg that leaves a scent on the ground, which helps them locate each other.

Reindeer's eyes change in winter. In summer, they have a golden reflective layer at the back of the eye, like a cat's eye. In winter, this layer turns dark blue, which means less light escapes and the eyes are more sensitive.

In this chapter you will study the ways in which thermal energy is transferred and how we can use this to our advantage.

Discussion questions

1 Human nasal passages also transfer thermal energy from exhaled air. Try breathing onto your hand, first from your mouth, then from your nose. You will notice the air from your nose is cooler. Discuss how we use this to help us cool down or to keep warm.

2 The reindeer's nasal passages can be referred to as a heat energy exchange system. They exchange the thermal energy from the warm hair breathed out to the cold air breathed in. Thermal energy exchangers can reduce the amount of fossil fuels we use, helping reduce the amount of energy we use and cutting costs. Discuss any other uses of thermal energy exchangers. These may be examples you have seen, or situations where you think they could be useful.

11.1 Conduction

As we discussed in Chapter 6, thermal energy transfers from a hotter place to a colder place, that is, from a higher temperature to a lower temperature. Thermal energy requires a temperature difference if it is to be transferred. In this chapter, we look at the various ways in which thermal energy is transferred. We start with thermal conduction.

Lying on the table are two spoons: one is metal, the other is wooden (Figure 11 4) You pick up the metal spoon – it feels cold. You pick up the wooden spoon – it feels warm. In fact, both are at the same temperature (room temperature) as a thermometer would prove to you.

How can this be? What you are detecting is the fact that metal is a good conductor of thermal energy, and wood is a poor conductor of thermal energy.

When your finger touches a metal object, thermal energy is conducted out of your finger and into the metal. Because metal is a good **thermal conductor**, thermal energy spreads rapidly through the metal. Thermal energy continues to escape from your finger, leaving it colder than before. The temperature-sensitive nerves in your finger tip tell your brain that your finger is cold. So, you think you are touching something cold.

When you touch a wooden object, thermal energy conducts into the area that your finger is in direct contact with. However, because wood is a good **thermal insulator**, the thermal energy travels no further. Your finger loses no more thermal energy and remains warm. The message from the nerves in your finger tip is that your finger is warm. So, you think you are touching something warm.

Note that the nerves in your finger tell you how hot your finger is, not how hot the object that you are touching is! This is similar to our discussion of thermometers in Chapter 10. A thermometer in water indicates its own temperature, and we have to assume that the temperature of the water is the same as this.

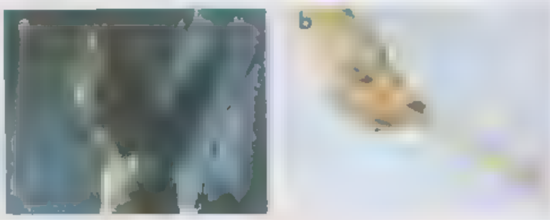


Figure 11.4a: Touching a metal spoon. **b:** Touching a wooden spoon

thermal conduction: the transfer of thermal energy by the vibration of molecules

thermal conductor: a substance that conducts thermal energy

thermal insulator: a substance that conducts very little thermal energy

EXPERIMENTAL SKILLS

Demonstrating conduction

In this series of experiments, you will investigate how materials conduct, and which are the best conductors. This information is vital for engineers and designers whose work involves planning how to keep temperatures safe and comfortable.

Safety: These experiments will involve heating materials to high temperatures. Plan carefully so that you can leave hot materials to cool safely. Wear safety goggles while using the Bunsen burner.

Carry out a risk assessment and make sure your teacher has checked it before beginning any practical work.

Getting started

Look at the apparatus in Figure 11.5. Explain how attaching paper clips using petroleum jelly will allow you to observe conduction.

Part 1: How is thermal energy conducted along a metal bar?

You will need:

- Bunsen burner
- heatproof mat
- clamp and stand
- copper rod
- paper clips
- petroleum jelly

CONTINUED

Method

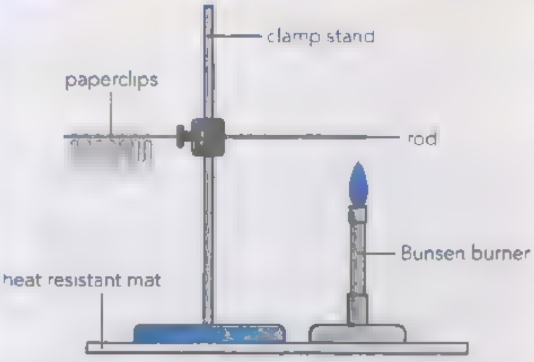


Figure 11.5: Experimental set-up for part 1

1. Use small blobs of petroleum jelly to attach paper clips along the copper rod, as shown in Figure 11.5.
2. Secure the rod in the clamp and heat the other end.
3. Watch carefully what happens to the paper clips.

Questions

1. Describe what happened to the paper clips.
2. What does this tell you about how thermal energy is conducted along the rod?

Part 2: Which metal is the best conductor?

You will need

- Bunsen burner
- heatproof mat
- tripod
- rods made from different metals
- paper clips
- timer
- petroleum jelly

Method

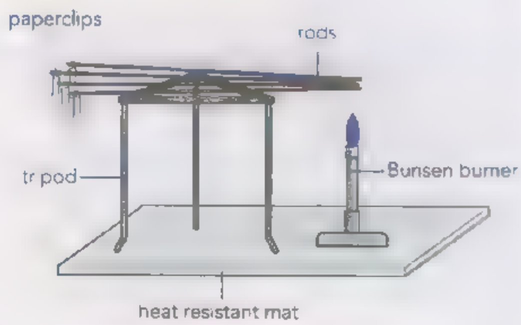


Figure 11.6: Experimental set-up for part 2

1. Use small blobs of petroleum jelly to attach a paper clip to the end of each metal rod.
2. Place the rods on the tripod, as shown in Figure 11.6, and heat the ends.
3. Use a table like this to record the time taken for each paper clip to fall.

Metal	Time taken for clip to fall / [illegible]

Questions

1. Write the metals in order from the best conductor to the worst conductor.
2. Do you think this was a fair test? Explain why or why not. Describe any possible sources of experimental error.

CONTINUED

Part 3: Is water a good conductor of thermal energy?

You will need:

- Bunsen burner
- heatproof mat
- boiling tube
- small piece of wire gauze
- test tube holder
- cold water
- ice cube

Method

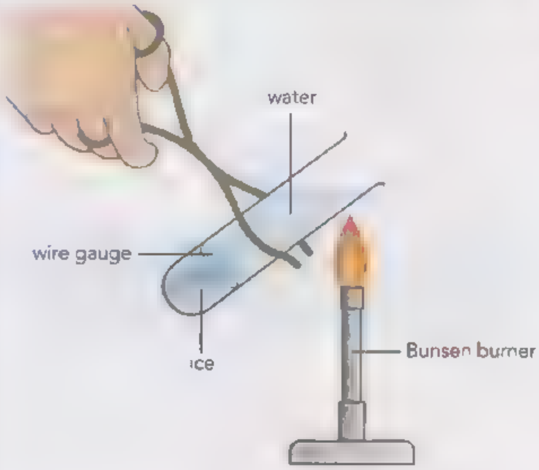


Figure 11.7: Experimental set up for part 3.

1 Fill three-quarters of the boiling tube with water. Add a small ice cube and then a small piece of wire gauze to hold the ice in place, as shown in Figure 11.7.

2 Look at the boiling tube. Touch it to check the temperature.

3 Hold the tube with the test tube holder and gently heat the water at the top of the tube.

4 Watch carefully to see what happens to the water at the top of the tube and to the ice.

Questions

1 Describe your observations.

2 Explain why this experiment shows that water is a poor conductor of thermal energy.

Part 4: What materials make good insulators?

You will need:

- 4 equal sized beakers with cardboard lids
- 4 thermometers, pushed through the cardboard lids
- timer
- a range of insulating materials
- electric kettle.

Method

Figure 11.8: Experimental set-up for part 4

1. Wrap three of the beakers in different insulating materials. Leave the fourth beaker without insulation.
2. Design a table to record your results.
3. Boil the kettle and carefully pour equal amounts of water into each of the beakers.
4. Measure the temperature of the water in each beaker every minute for ten minutes.

Questions

1. Why was the beaker with no insulation included in the experiment?
2. Draw a graph of your results. Plot temperature on the *y*-axis against time on the *x*-axis. Plot all four sets of results on the same axis.
3. Which insulator kept the water the hottest?
4. List the insulators in order from best to worst.

Think about the experiments you have done and write a short sentence to sum up what you have learnt in each. What was the most powerful learning moment for you in these experiments? Think about why this was and how it helped your understanding.

Table 11.1 compares conductors and insulators. In general, metals are good conductors of thermal energy and non-metals are poor conductors. Air and water are very poor conductors of thermal energy.

best conductor ↓		*worst insulator* ↑
	diamond	
	silver, copper	
	aluminum, steel	
	lead	
	ice, marble, glass	
	polyethene, nylon	
	rubber, wood	
	polystyrene	
worst conductor	glass wool	*best insulator*

Table 11.1: Comparing conductors of thermal energy, from the best conductors to the worst. A bad conductor is a good insulator. Almost all good conductors are metals; polymers (plastics) are at the bottom of the list. Glass wool is an excellent insulator because it is mostly air.

Explaining conduction in metals and non-metals

Both metals and non-metals conduct thermal energy. Metals are generally much better conductors than non metals. We need different explanations of conduction for these two types of material.

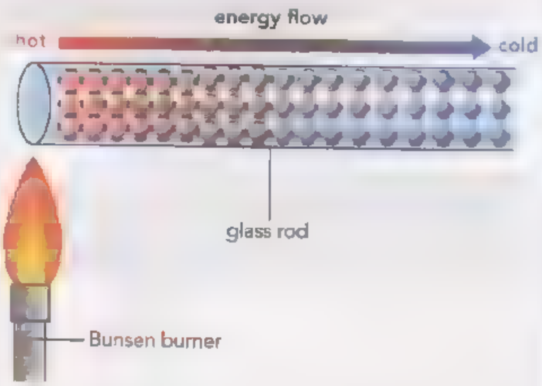


Figure 11.9: Conduction of thermal energy in non-metals. A glass rod is heated at one end. Thermal energy travels from the hot end to the cold end.

We will start with non-metals. Imagine a long glass rod (Figure 11.9). One end is being heated, the other end is cold. This makes a temperature difference between the two ends, and so thermal energy flows along the rod. What is going on inside the rod?

Look at the particles inside the rod in Figure 11.9. At the hot end of the rod, the atoms are vibrating much more than they are at the cold end. As the atoms vibrate, they collide with their neighbours. This process results in each atom sharing its energy with its neighbouring atoms. Atoms with a lot of energy end up with less, and those with a little end up with more. The collisions gradually transfer energy from the atoms at the hot end to those at the cold end. Energy is steadily transferred down the rod, from the hot end to the cold end.

This is how poor conductors (such as glass, ice and plastic) conduct thermal energy. It is not a very efficient method of thermal energy transfer.

Metals are good conductors for another reason. Many of the **electrons** in metallic conductors are free to move (they are delocalised). These are the particles which carry electric current. They also carry thermal energy as they get hot and move through the metal. Figure 11.10 shows a copper rod, heated in the same way as the glass rod. Notice the free electrons, which carry thermal energy through the metal.

electron: a negatively charged particle, smaller than an atom

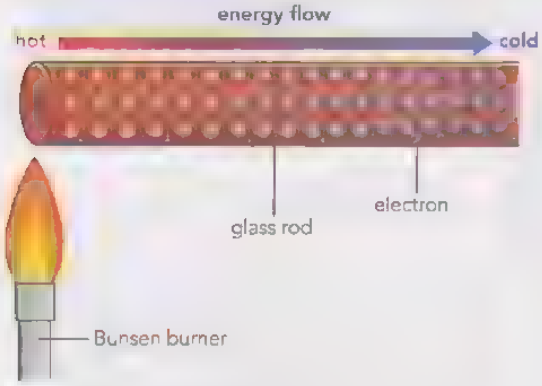


Figure 11.10: Conduction of thermal energy in metals. Metals have free electrons which carry thermal energy, making metals good conductors.

Liquids can also conduct thermal energy, because the particles of which they are made are in close contact with one another. However, as the particles are free to move, vibrations are not passed on as easily as in a solid. The particles in gases are very spread out, making gases very poor conductors of thermal energy.

Questions

1 Copy these sentences. Choose the correct word from each set of brackets.

Conduction happens mostly in {solids / liquids / gases}. Thermal energy flows from the {hotter / cooler} parts of an object to the {hotter / cooler} parts. A material which does not conduct thermal energy well is called {a conductor / an insulator / a resistor}. An example is {copper / polystyrene / gold}.

2 Explain why a wooden spoon is better than a metal one to stir a saucepan of hot soup.

3 Use the information in Table 11.1 to explain why walking on a marble floor in bare feet would feel colder than walking on a wooden floor.

4 Explain why two thin layers of clothing are often warmer than one thick layer.

5 Explain why:

a copper is a better conductor than wood

b wood is a better conductor than air

11.2 Convection

As we have seen, liquids and gases are not usually good conductors of thermal energy. Thermal energy transfer in liquids and gases is mainly by another method known as convection.

Figure 11.11: The heater is heating the air going into the balloon. This makes the air expand so it becomes less dense and makes the balloon float up.

'Hot air rises' is a popular saying one of the things many adults remember from their science lessons. Figure 11.11 shows this science being put to use. When air is heated, it expands and so its density decreases. The warm air is less dense than its surroundings, so it floats upwards. For the balloon to rise, the density of the hot air, the balloon itself, plus the basket and its occupants, must altogether have a density less than that of the surrounding cold air

The opposite effect can be seen in Figure 11.12 Cold air sinks. This photo is taken with a technique which shows the flow of air You can see cold air sinking down below the frozen pizza.

Figure 11.12: Cold air sinks below any object which is colder than its surroundings.

The rising of hot air is just one example of **convection**. Hot air can rise because air is a **fluid**, and convection can be observed in any fluid any (liquid or gas). Convection doesn't happen in solids as the particles are in fixed positions so they cannot flow.

Figure 11 13 shows how a convection current can be observed in water. Above the flame, water is heated and expands. Now its **density** is less than that of the surrounding water, and it floats upwards. The purple dye shows how it moves. Colder water, which is more dense, flows in to replace it.

A **convection current** is a movement of a fluid that carries energy from a warmer place to a cooler one. This highlights an important difference between convection and conduction.

- In convection, energy is transferred through a material from a warmer place to a cooler place by the movement of the material itself.
- In conduction, energy is transferred through a material from a warmer place to a cooler place without the material itself moving.

convection the transfer of thermal energy through a material by the movement of the material itself

fluid: a substance which can flow; liquids and gases are fluids

density: the ratio of mass to volume for a substance

convection current: the transfer of thermal energy by the motion of a fluid

Figure 11.13: Because water is clear and colourless, it can be difficult to see how the water moves to form a convection current. Crystals of potassium manganate(VII) act as a purple dye to show the movement of the water.

Demonstrating convection

Convection in air and water is difficult to see as air and water are transparent and colourless. These experiments will let you observe convection currents in water and air.

You will need

- Bunsen burner
- heatproof mat
- tripod
- beaker
- tweezers
- thin card
- scissors
- thin thread
- potassium manganate(VII) crystals

Safety: Wear eye protection when using a Bunsen burner. Wear protective gloves when handling potassium manganate(VII). Do not hold the card spiral near a flame.

Getting started

What is the purpose of the potassium manganate(VII) crystal in this experiment?

Method part 1: Convection in a liquid

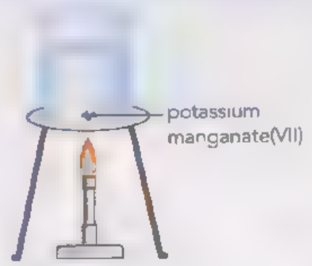


Figure 11.14: Set-up for experiment.

1. Fill three-quarters of a beaker with water.
2. When the water is settled, use tweezers to place two or three small crystals of potassium manganate(VII) on the bottom of the beaker, at one side. (See Figure 11.14.)
3. Use a Bunsen burner to heat the water gently, just below the crystals.
4. Observe what happens to the colour of the potassium manganate(VII) as it moves. This shows how the water is flowing.

Method part 2: Convection in air

Figure 11.15: Cutting a spiral and using it to demonstrate convection.

1. Cut a spiral from thin card.
2. Attach a thin thread to the centre of the spiral.
3. Hold the thread above a heat source (such as a radiator) and observe how it moves.

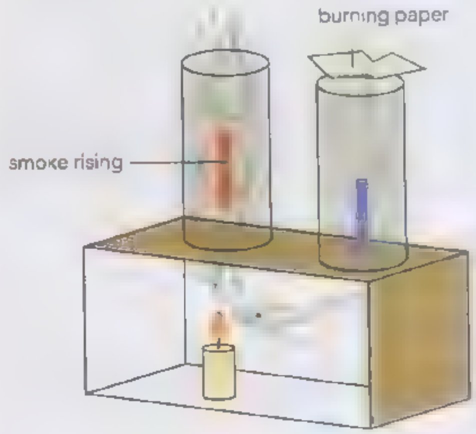


Figure 11.16: Experiment with candle and burning paper

Questions

1. Draw the beaker of water and arrows to show the movement of the purple colour when you heated it.
2. The experiment shown in Figure 11.16 uses smoke from burning paper to show convection currents in air. Explain why the smoke moves down one chimney and up the other.

Convection currents at work

Convection currents help to share energy between warm and cold places. If you are sitting in a room with an electric heater, thermal energy will be moving around the room from the heater as a result of convection currents, which rise from the heater. You are likely to be the source of convection currents yourself, since your body is usually warmer than your surroundings (see Figure 11.21) Many biting insects make use of this effect. For example, bed bugs crawl across the bedroom ceiling They can detect a sleeping person below by finding the warmest spot on the ceiling. Then they drop straight down on to the sleeper. This is a lot easier than crawling about on top of the bedding.

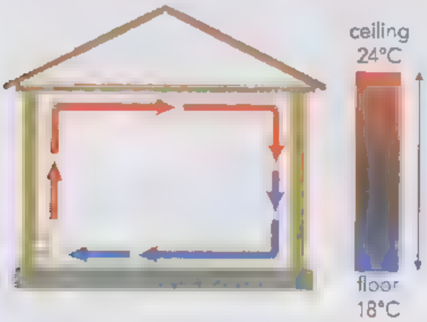


Figure 11.17: Convection currents rise above the warm objects in a room.

Cold objects also produce convection currents. You may have noticed cold water sinking below an ice cube in a drink. In a refrigerator, the freezing surface is usually positioned at the top and the back, so that cold air will sink to the bottom. Warm air rises to replace the cold air as it sinks. The warm air is then cooled. (see Figure 11.18)

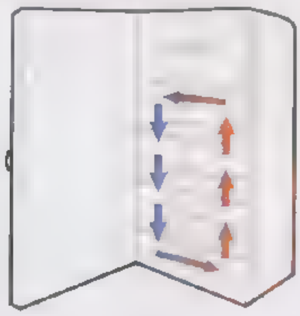


Figure 11.18: In a refrigerator, cold air sinks from the freezing compartment. If the freezer was at the bottom, cold air would remain there, and the food at the top would not be cooled

Explaining convection

We have already seen that convection results from the expansion of a fluid when it is heated. Expansion means an increase in volume while mass stays constant. This means that density decreases. A less dense material is lighter and so is pushed upwards by the surrounding denser material.

The particles in the hotter fluid have more kinetic energy so they move around faster. As they flow from place to place, they take this energy with them.

Convection is the main method of thermal energy transfer in fluids. Thermal energy can be conducted through a liquid but this is generally a slow process compared with convection.

Questions

6 Copy Figure 11.19. Add arrows labelled 'cold dense water' and 'hot, less dense water' to show the convection current in the pan

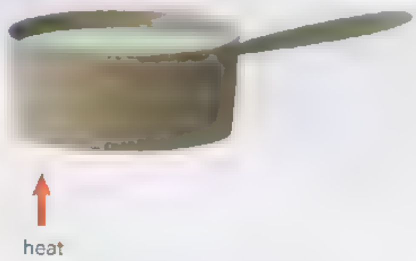


Figure 11.19: A pan of water

7 The ice cube in Figure 11.20 floats at the top of the water. Draw and label a diagram to show how the ice cube creates a convection current which cools al of the water

Figure 11.20: Ice in glass of water

8 An inventor makes an electric kettle with the heating element at the top. Explain why it will not work.

9 a Draw diagrams to show the difference in the arrangement of particles in a hot gas and a cold gas.

b Use your diagrams to explain why hot gases rise. Use the words 'expand' and 'density' in your answer.

10 Explain why convection does not happen in solids.

11.3 Radiation

At night, when it is dark, you can see much further than during the day. In the daytime, the most distant object you are likely to be able to see is the Sun, about 150 million kilometres away. At night, you can see much further, to the distant stars. The most distant object visible to the naked eye is the Andromeda galaxy, about 20 million million million kilometres away.

The light that reaches us from the Sun and other stars travels to us through space in the form of electromagnetic radiation. This radiation travels as electromagnetic waves. It travels over vast distances, following a straight line through empty space. Radiation is the only form of thermal energy transfer which does not involve the movement of particles. Thermal radiation does not need a medium to travel through. It can travel through a vacuum. As well as light, the Earth receives other forms of electromagnetic radiation from the Sun, including infrared and ultraviolet radiation. (You will learn much more about electromagnetic radiation in Chapter 15.)

All objects emit **infrared radiation**. The hotter an object, the more infrared radiation it gives out. You can use this idea to help you to do a bit of detective work. Imagine you arrive at a crime scene. The suspect says he has just arrived by car. You suspect he has been at the scene for an hour, giving him time to commit the crime. Holding your hand over the engine compartment will quickly tell you if the engine is radiating thermal energy.

KEY WORDS

infrared radiation: electromagnetic radiation with a wavelength greater than that of visible light; sometimes known as thermal energy radiation

Our skin detects the infrared radiation produced by a hot object. Nerve cells just below the surface respond to thermal energy. You notice this if you are outdoors on a sunny day.

To summarise, infrared radiation:

- is produced by warm or hot objects
- is a form of electromagnetic radiation
- travels through empty space (and through air) in the form of waves
- travels in straight lines
- warms the object that absorbs it
- is invisible to the naked eye
- can be detected by nerve cells in the skin.

Figure 11.21: Using an infrared-sensitive camera. Slight variations in temperature show up as different colours. The scale shows how the colour relates to temperature.

Figure 11.21 shows another way of detecting infrared radiation: by using a temperature-sensitive camera. The photograph of a woman sitting at a desk is taken with a camera which detects infrared radiation instead of light. It is very sensitive to slight differences in temperature.

Questions

11 Which statement about infrared radiation is true?

A Infrared radiation travels slower than light.

B Infrared radiation cannot be reflected.

C Infrared radiation can travel through a vacuum.

D Infrared radiation is transferred by the movement of particles.

12 Explain why thermal energy from the Sun can only reach us by radiation, not conduction or convection.

13 What evidence is there in this infrared photograph (Figure 11.22) to suggest that the car has only just broken down?

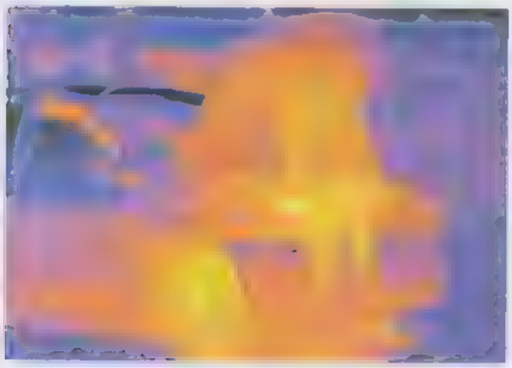


Figure 11.22: nfrared photograph of a car

ACTIVITY 9.1

Thermal imaging

Figure 11.23: Thermal image of a fingerpr nt.

A sc ence museum is preparing a display about infrared photography. You are a researcher and have been given the fol owing brief.

Investigate one of the uses of this technology and prepare an information board about it. Your board should be one s de of A4 paper. It must include at least one eye-catching picture taken with an infrared camera, and a maximum of 150 words describing the science and how it s used.

CONTINUED

The board should be interesting to the general public and also detailed enough to be relevant to h gh school phys cs students.

Uses of infrared technology include:

- medic ne
- military
- detection of drug farms
- astronomy
- wildlife photography
- forensic science
- studying thermal energy loss from buildings.

[illegible]

Display each group's work from Activity 9.1 around the classroom. Take a class vote on which board best meets the brief. Discuss what makes it a good piece of work. Adapt your board to add some of the features you identified

Good absorbers, good emitters

Figure 11.24: A sunshield reflects unwanted radiation, which wou d otherwise make the car very hot

On a hot, sunny day, car drivers may park their cars with a sunshield behind the windscreen (Figure 11.24). Such a sunshield is usually shiny, because this reflects light and infrared radiation from the Sun. This stops the car getting uncomfortably hot The black plastic parts of the car (such as the steering wheel and dashboard) are very good absorbers of infrared radaition, and they can become too hot to touch.

It is the surface that determines whether an object absorbs or reflects infrared radiation. A surface that is a good reflector is a poor absorber. On a hot day, you may have noticed how the black surface of a tarred (metalled) road emits thermal energy. Black surfaces readily absorb infrared radiation. They are also good emitters.

You may also have noticed that you stay cooler on a hot day if you wear light coloured clothes. Light surfaces do not absorb much thermal radiation. Instead, they reflect the radiation. The house in Figure 11.25 is painted white to reflect infrared radiation.

- Shiny or white surfaces are the best reflectors (the worst absorbers).
- Matte black surfaces are the best absorbers (the worst reflectors).
- Matte black surfaces are the best emitters.

Figure 11.25: This house is built from bottles filled with sand. It is painted white to reduce absorption of infrared radiation.

Questions

14 Explain why the worker in Figure 11.26 is wearing a shiny suit.

Figure 11.26: A worker supervising the flow of hot molten metal

15 Which will stay hot longer: tea in a shiny silver teapot or tea in dark brown one? Explain your answer.

Factors affecting infrared radiation

All objects emit radiation and absorb radiation from their surroundings. The hotter an object is, the more radiation it emits each second, or the more power it radiates. Any object which is hotter than its surroundings radiates more energy per second than it absorbs and so will cool down. An object which is cooler than its surroundings absorbs more energy per second than it radiates until it reaches the temperature of its surroundings. An object with a temperature that remains constant absorbs thermal energy at the same rate as it emits thermal energy. An object with a large surface area emits thermal energy at faster rate.

Figure 11.27 shows three beakers of water. The room temperature is 20 °C. All three beakers radiate and absorb energy, but the amount of radiation and absorption depends on the temperature.

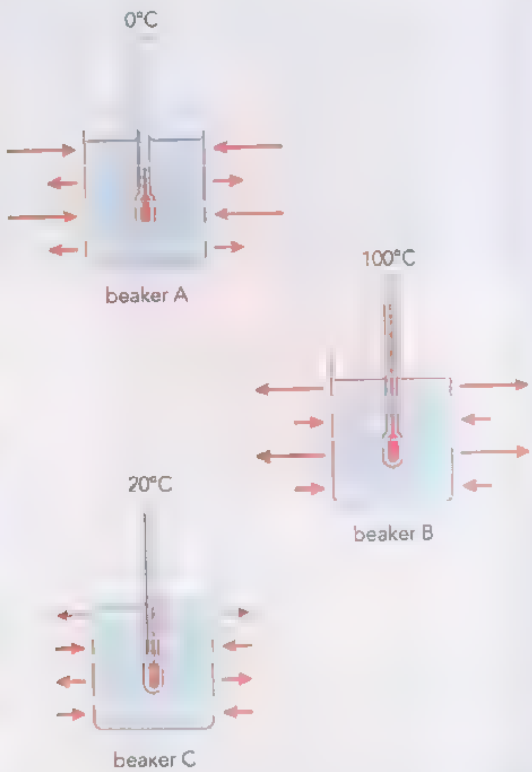


Figure 11.27: Beaker A will warm up, beaker B will cool down and beaker C will remain at a constant temperature

Investigating the emission and absorption of infrared radiation

In this investigation you will use cans of water with different surfaces to investigate which emits most infrared radiation and which absorbs most infrared radiation.

The amount of infrared radiation emitted also depends on the surface area and temperature of the objects so these must be controlled in your experiment.

You will need

- 1 shiny silver can and 1 dull black can
- 2 lids with holes for thermometers
- 2 thermometers or electronic temperature probes
- timer
- kettle
- board to isolate the cans from each other
- Bunsen burner or electrical heater.

Safety: Take care when using hot water. Do not touch or move the cans while they are full of very hot water. Wear eye protection when using a Bunsen burner.

Getting started

Look at Figure 11.28. Use what you know about thermal energy transfers to explain why the cans must be fitted with lids, and why they should stand on a wooden or plastic surface.

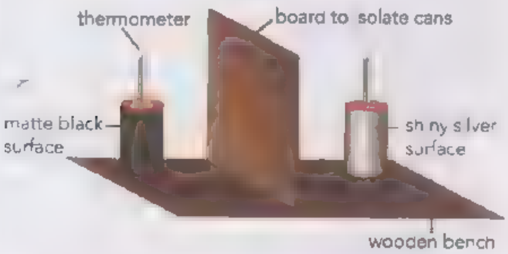


Figure 11.28: Set-up for the experiment.

Experiment A: Which surface radiates better, black or shiny?

Method

1. Set up the experiment as shown in Figure 11.28
2. Fill the two cans with equal volumes of hot water.
3. Use thermometers or electronic temperature probes to measure the temperature of the water in each can every minute for ten minutes.

Questions

1. What features of the experimental design ensure that this is a fair test?
2. Plot a graph of temperature on the y-axis against time on the x-axis. Plot both sets of results on the same graph.
3. What can you conclude from your results?

Experiment B: Which surface absorbs thermal energy better, black or shiny?

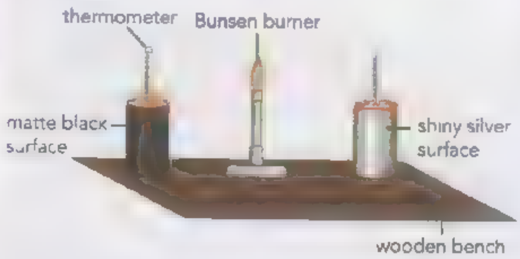


Figure 11.29: Set-up for the experiment

Method

1. Set up the experiment as shown in Figure 11.29; use the same cans as in experiment A.
2. Fill the cans with equal volumes of cold water
3. Place the cans at equal distances from the Bunsen flame or electric heater.
4. Use thermometers or electronic temperature probes to measure the temperature of the water in each can every minute for ten minutes.

Questions

1. Plot a similar graph to experiment A.
2. What can you conclude from your results?

11.4 Consequences of *thermal energy transfer*

In this section, we will see how we can use ideas about thermal energy transfers to understand a lot of different situations. Remember that:

- Thermal energy travels from a hotter place to a colder place. It is the temperature difference that makes it flow
- Conduction is the main way in which energy can pass through a solid. Energy travels through the solid but the solid itself cannot move.
- Convection is the main way in which energy is transferred in a fluid. Warm fluid moves around, carrying energy with it.
- Radiation is the only way in which thermal energy can travel through empty space. Infrared radiation can also pass through some transparent materials such as air.

Hot objects have a lot of internal energy. As we have seen, energy tends to escape from a hot object, spreading to its cooler surroundings by conduction, convection and radiation. This can be a great problem. We may use a lot of energy (and money) to heat our homes during cold weather, and the energy simply escapes. We eat food to supply the energy we need to keep our bodies warm, but energy escapes from us at a rate of about 100 watts (100 W = 100 J/s).

To keep energy in something that is hotter than its surroundings, we need to insulate it. Knowing about conduction, convection and radiation can help us to design effective insulation.

Remember that all three mechanisms of energy transfer (conduction, convection and radiation) may be involved when an object warms up or cools down.

Home insulation

A well-insulated house can avoid a lot of energy wastage during cold weather. Insulation can also help to prevent the house from becoming uncomfortably hot during warm weather. Figure 11.30 shows where thermal energy is lost from a house, and some ways to reduce thermal energy losses. More details are listed in Table 11.2.

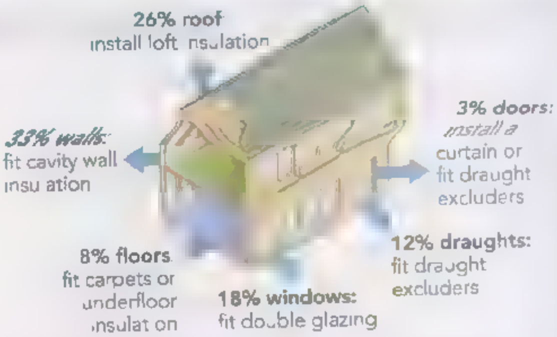


Figure 11.30: Insulating a house reduces thermal energy loss and heating costs.

Method		Why it works
	thick curtains, draught excluders	stops convection currents, and so prevents thermal energy transfer
	loft and underfloor insulating materials	prevents conduction of thermal energy through floors and ceilings
	double and triple glazing of windows	vacuum between glass panes cuts out losses or gains by conduction and convection
	cavity walls	reduces thermal energy loss or gain by conduction
	foam or rockwool in wall cavity	further reduces thermal energy transfer by convection

Table 11.2: Methods of retaining energy in a house in a cold climate, and of keeping a house cool in a hot climate

Double-glazed windows usually have a vacuum between the two panes of glass. This means that energy can only escape by radiation, since conduction and convection both require a material. Modern houses are often built with cavity walls, with an air gap between the two layers of bricks. It is impossible to have a vacuum in the cavity, and convection currents can transfer energy across the gap (see Figure 11.31a). Filling the cavity with foam means that a small amount of energy is lost by conduction, although the foam is a very poor conductor. However, this does stop convection currents from flowing (Figure 11.31b), so there is an overall benefit.

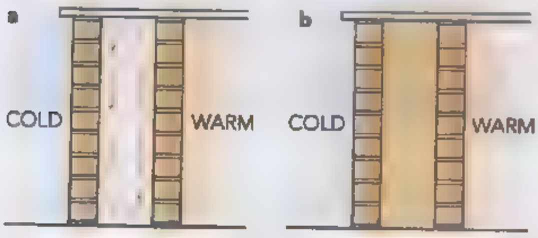


Figure 11.31a: A cavity wall reduces thermal energy loss by conduction because air is a good insulator. However, a convection current can transfer energy from the inner wall to the outer wall. **b:** Filling the cavity with foam or mineral (glass or rock) wool prevents convection currents from forming.

Keeping cool

Vacuum flasks are used to keep hot drinks hot. They can also be used to keep cold drinks cold. Giant vacuum flasks are used to store liquid nitrogen and helium at very low temperatures, ready for use in such applications as body scanners in hospitals. They also have medical uses, such as for storing frozen embryos for IVF treatment.

Figure 11.32 shows the construction of a vacuum flask. Glass is generally used, because glass is a good insulator. However, some flasks are made of steel for added strength. Air is removed from the gap between the double walls, creating a vacuum. This reduces losses by conduction and convection because both of them need a material to travel through. The silver coating on the glass reduces losses by radiation by reflecting any infrared radiation. The stopper is made of plastic and it prevents losses by convection and evaporation.

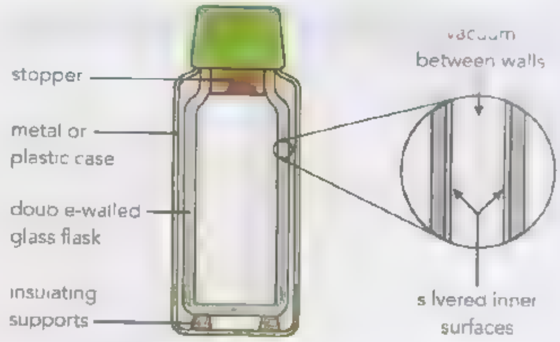


Figure 11.32: A vacuum flask is cleverly designed to keep hot things hot by reducing thermal energy losses. It also keeps cold things cold. Although we might say 'it stops the cold getting out', it is more correct to say that it prevents thermal energy from getting in. The first such flask was designed by James Dewar, a Scottish physicist, in the 1870s. He needed flasks to store liquefied air and other gases at temperatures as low as −200 °C. Soon after, people realised that a flask like this was also useful for taking hot or cold drinks on a picnic.

Figure 11.33: This couple are hoping to have a baby by IVF. The flask they are holding contains their frozen embryos.

ACTIVITY

Marketing a vacuum flask

Imagine you have just invented the vacuum flask. You want to go into business producing and selling flasks but need finance. Prepare a presentation for potential investors. You will need to explain the technical details of how it works. You must use the words 'conduction', 'convection' and 'radiation'. The investors want to know you are an expert and understand the science. You should also explain why your product will be popular with customers.

Your presentation can include an information leaflet, a video or an advertising poster.

A car engine burns fuel and so gets very hot. The cooling system (Figure 11.34a) transfers some of this thermal energy to the surroundings so the engine does not overheat. This system uses many of the things you have learnt.

- Specific heat capacity: water flows around the block to absorb thermal energy. Water is a good choice as it has a very high specific heat capacity.
- Convection: as the water is heated, a convection current flows in the direction shown by the arrows. The pump is used to speed up this flow.
- Conduction: the radiator has metal fins (Figure 11.34b) so the thermal energy is conducted to all parts of the radiator.
- Radiation: the fins have a large surface area and are black to increase the rate of thermal energy radiation.

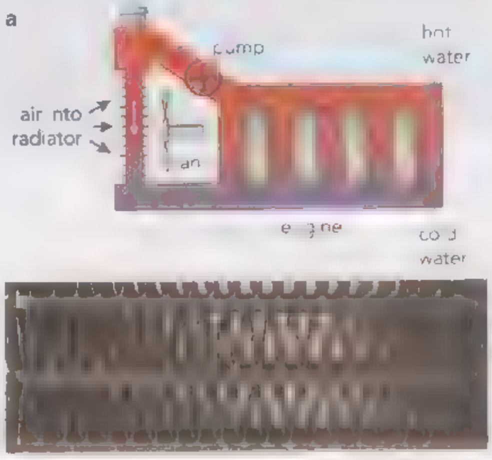


Figure 11.34a: Transfer of thermal energy in a car cooling system. b: The black metal radiator cooler fins in a car.

Wood burns on a bonfire to produce thermal energy. The heating effect you experience when sitting by a fire is almost entirely due to radiation. Air is a bad conductor and thermal energy transfer due to convection will heat the air above the fire.

Figure 11.35: The older child will feel hotter than the younger child as his black T-shirt absorbs infrared radiation whereas the white T-shirt reflects the infrared radiation.

Thermal energy transfer, climate and weather

Radiation from the Sun is essential for life on Earth. The Sun's radiation warms the Earth. The warm Earth emits some infrared radiation. Gases in the Earth's atmosphere, such as carbon dioxide, absorb some of the thermal energy and this warms our atmosphere. This is the greenhouse effect (Figure 11.36) and without it life on Earth would be impossible. However, the amount of greenhouse gases in the atmosphere is increasing, trapping more thermal energy. This means that Earth and its atmosphere are absorbing more infrared radiation than they emit. This is the cause of global warming.

Figure 11.36: For the Earth to maintain a constant temperature, infrared radiation must be emitted at the same rate as it is absorbed. Upsetting this balance is causing global warming.

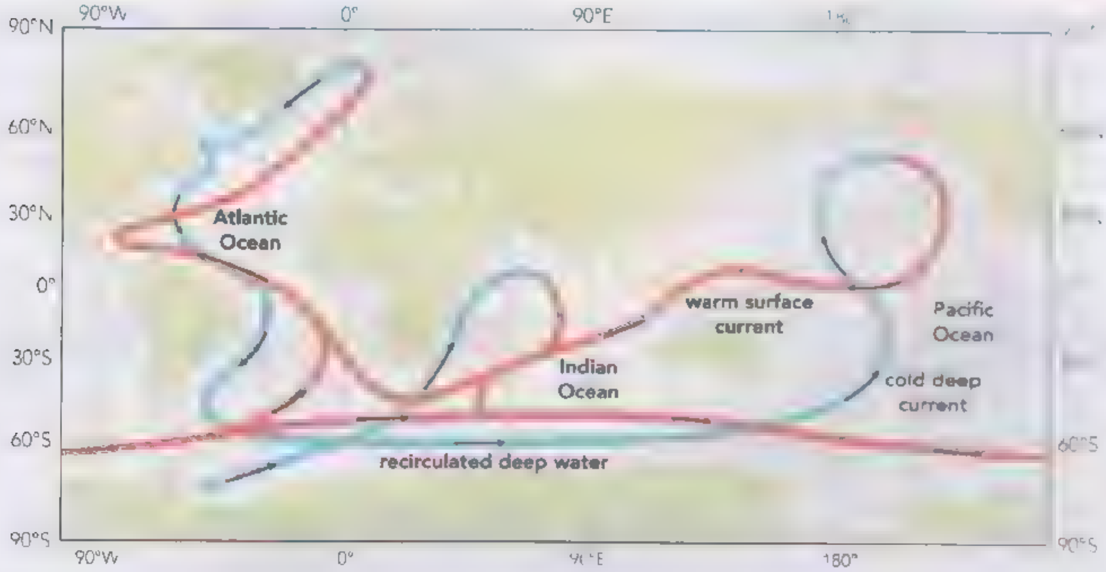


Figure 11.37: Convection currents in the oceans flow in predictable directions. The red lines show warm surface water and the blue lines show the flow of the deeper, colder water. The warm currents affect the climate. For example, the British Isles are warmed by the Gulf steam (a flow of warm water from the Gulf of Mexico).

Convection currents explain the origins of winds and ocean currents, which are two of the major factors that control climate patterns around the world. For example, warm air rises above the Equator, and colder air sinks in subtropical areas. This creates the pattern of trade winds that are experienced in the tropics.

Ocean currents (Figure 11.37) help to spread thermal energy from equatorial regions to cooler parts of the Earth's surface. Warm water at the surface of the sea flows towards the poles. In polar regions, colder water sinks and flows back towards the Equator. Provided this pattern remains constant, this helps to make temperate regions of the world more habitable. However, there is evidence that the pattern of ocean currents is changing, perhaps as a consequence of global warming.

Questions

16 **In a rolling mill, iron is heated to make it malleable and it is then passed through rollers to produce thin sheets of the metal. Explain how the following become hot in this process:**

- **a** the rollers which press the metal
- **b** the face of a worker
- **c** the air in the building.

17 **The coat in Figure 11.38 is designed for a cold climate.**

Figure 11.38

Describe the features of the coat which prevent thermal energy loss by:

- **a** conduction
- **b** convection
- **c** radiation.

18 Figure 11.39 shows a solar water heater. Cold water flows through the pipes and is heated by the Sun.

Suggest reasons why:

a the inside of the panel is painted black

b the back of the panel is insulated

c the cold water enters at the bottom of the panel, and leaves at the top.

Figure 11.39: A solar water heater

PROJECT

Be the teacher

A student has submitted their answers to a homework question. As you will see, they have not understood the topic. Your task is to:

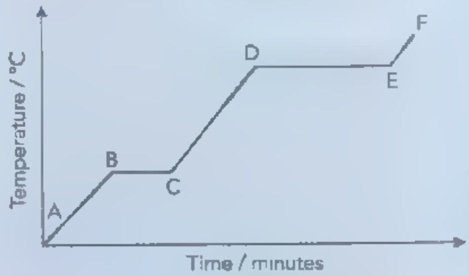
- Mark their work and identify any mistakes. Is there anything that shows they have been listening in class? Write brief encouraging feedback notes so the student will be willing to try again. Discuss with your group where the student is going wrong and what you might do to help them avoid making this mistake again.
- Write a model answer. Each member of the group should do this individually, then as a group, share your ideas and make sure you have the best possible answer.
- Plan a five minute revision session in which you explain the main points the student has missed. You can do this using presentation software, a short video, an illustrated talk or you could demonstrate some experiments (check with your teacher). Include study hints on how to remember key points as well as the factual information. Make your presentation as lively and relevant as you can.
- Deliver this revision session to another group of students.
- Prepare a follow up worksheet, with answers, to check that the students have understood your presentation.

Homework questions

1 The photograph shows a reusable insulated coffee cup.

Explain how the cup reduces thermal energy loss by conduction, convection and radiation.

2 A student heats some ice. She records the temperature and plots a graph.



Describe what is happening at each stage of the graph and identify any important temperatures.

Student's answers

1 The cup keeps the coffee hot because it is made of metal and metal is a good insulator so no thermal energy transfers through the metal walls.

The silver sides stop it cooling by radiation because any thermal energy from the Sun will be reflected away and will not affect the coffee. Silver surfaces reflect infrared radiation.

There is no thermal energy loss due to convection because the cup is solid. This means its particles are fixed in place and so convection currents can't happen.

2 A–B the ice is melting, B–C she has stopped heating the ice, C–D the water is getting hotter, D–E she has stopped heating it again, E–F the water is getting really hot. There are no numbers on the graph so I can't identify any temperatures.

PEER ASSESSMENT

Once your peers have completed your worksheet, read their answers and give them feedback. Comment on how well they use scientific terms, and how clear their explanations are.

What problems did you encounter while working on this project?

Did playing the part of the teacher tell you anything about the way you learn?

Metals are good thermal conductors. Most non-metals are good insulators.
Metals are good thermal conductors because they have free electrons.
Hot fluids are less dense than cold fluids. This causes convection currents.
Infrared radiation transfers thermal energy using electromagnetic waves.
Infrared radiation does not require a medium (it can travel through a vacuum).
Shiny, white surfaces reflect infrared radiation. They are poor emitters and absorbers of infrared radiation.
Dull, black surfaces are good absorbers and emitters of infrared radiation, but poor reflectors.
The amount of infrared radiation emitted also depends on the surface area and temperature of the object

EXAM-STYLE QUESTIONS

1 Which word describes a material that does not let thermal energy pass through it? [1]

A conductor
B vacuum
C resistor
D insulator

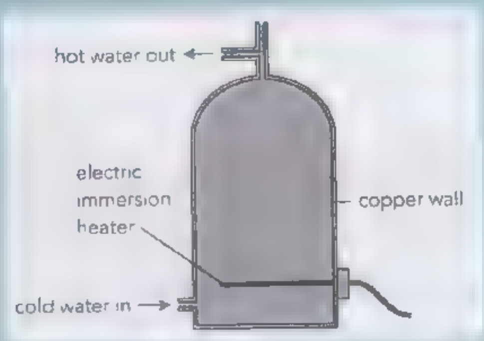
2 Which states of matter can convention happen in? [1]

A solids and liquids
B liquids and gases
C gases and solids
D solids, liquids and gases

3 Hot fluids rise. This can be explained because, as the fluid gets hotter, there is a decrease in the fluid's: [1]

A mass
B temperature
C density
D volume

4 This diagram shows an electric water heater.



a The copper wall is hot to touch. Name the process by which thermal energy from the water passes through the wall. [1]

b Describe how a heater at the bottom of the tank heats all the water in the tank. [3]

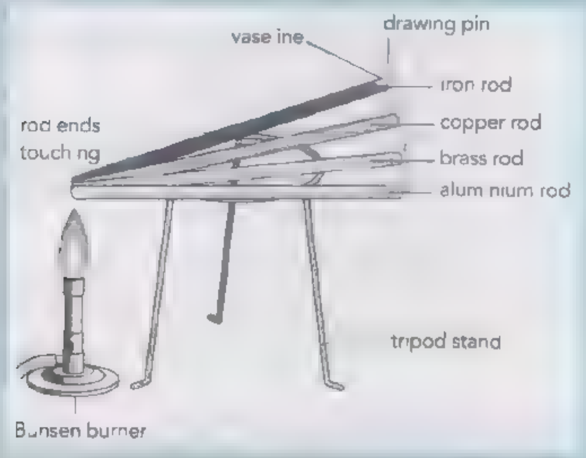
c The hot walls transfer thermal energy to the surroundings. Suggest a way this thermal energy loss could be reduced. [1]

[Total: 5]

describe: state the points of a topic; give characteristics and main features

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations

5 a Suggest a question which can be answered using the apparatus in the diagram. [1]

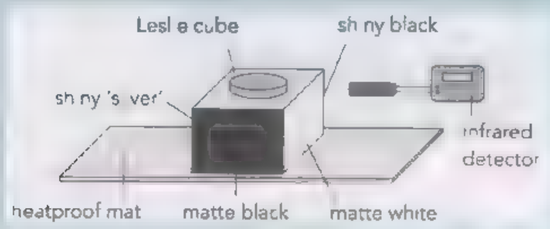


b **Explain** which rod you would expect the drawing pin to fall from first. [2]

c Describe two features of the experiment which make it a fair test. [2]

[Total: 5]

6 The diagram shows a Leslie cube. It is a metal box and each side has a different surface.



Saraya uses a Leslie cube to investigate infrared radiation. She fills the cube with boiling water so all sides are at the same temperature. She uses the infrared detector to investigate the radiation from each surface.

a Why is it important to keep the detector the same distance from each side? [1]

b Match the surfaces to the temperatures. The first one has been done for you. [2]

shiny black	64.5 °C
matte black	71.2 °C
shiny silver	60.4 °C
matte white	65.3 °C

explain: set out purposes or reasons / make the relationships between things evident / provide why and / or how and support with relevant evidence

c Saraya's infrared detector gave the temperature to the nearest 0.1 °C.

Zain repeats the experiment using a different infrared detector which gives the temperature to the nearest degree.

Suggest how Zain's conclusion will differ from Saraya's. [2]

[Total: 5]

7 Some double glazed windows have a plastic frame and two panes of glass with a vacuum between them.

a Explain why plastic is used for the frame. [1]

b Name the types of thermal energy transfer which are stopped by the vacuum. [2]

c Double glazing reduces thermal energy losses from a house. Describe two other ways to reduce thermal energy losses and [illegible] the type of thermal energy transfer which each reduces. [4]

[Total: 7]

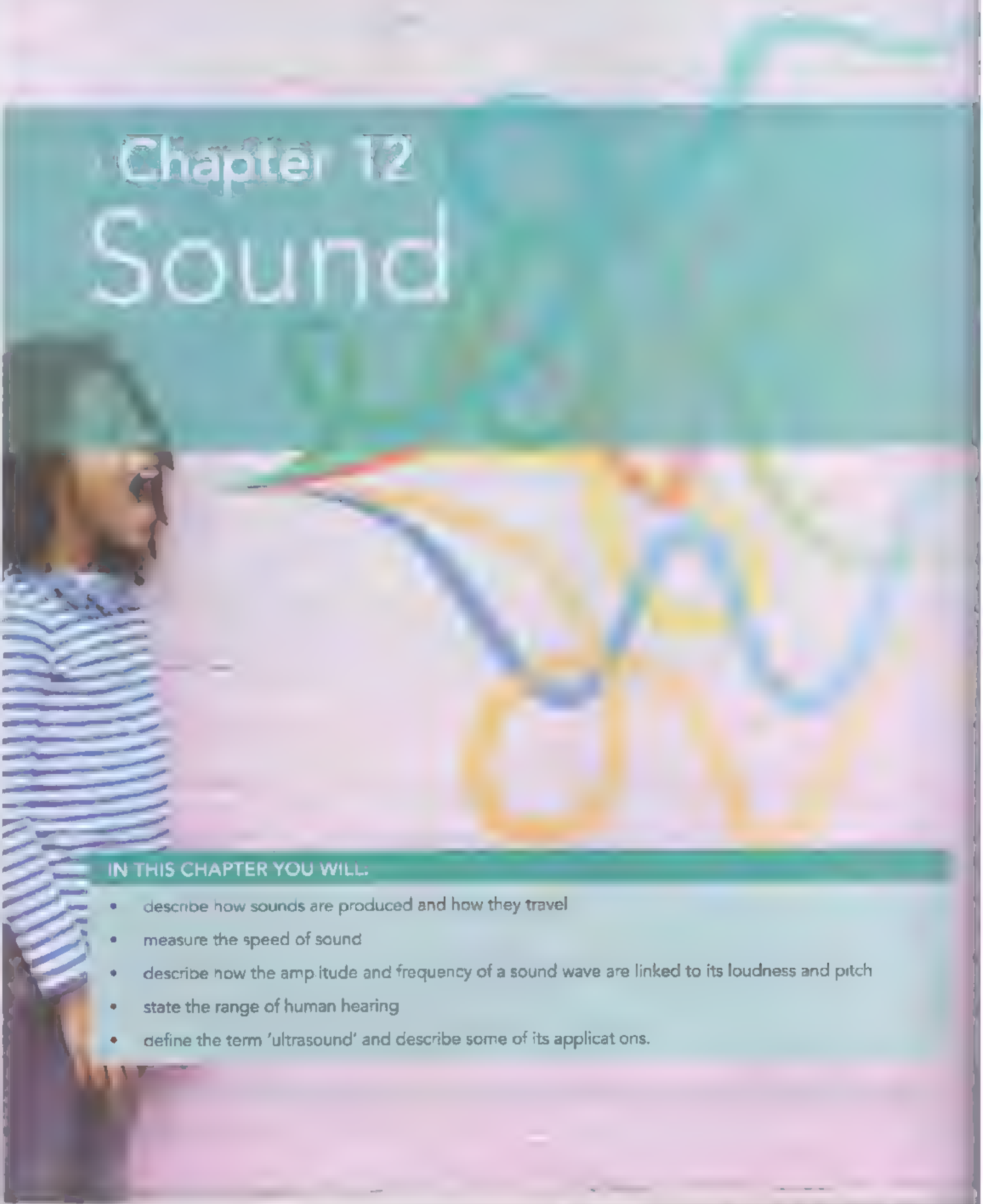
state: express in clear terms

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	[illegible]	[illegible]	[illegible]	[illegible] to move on
Describe experiments to show the properties of conductors and insulators.	11.1			
Explain thermal conduction in metallic conductors in terms of free electrons.	11.1			
State that thermal energy is transferred by convection in fluids.	11.2			
Explain how changes in density cause convection currents.	11.2			
Describe experiments to demonstrate convection.	11.2			
Describe experiments to demonstrate convection	11.2			
State that infrared radiation is a part of the electromagnetic spectrum and can pass through a vacuum	11.3			
Describe how the surface of an object affects how it emits, reflects or absorbs infrared radiation.	11.3			
Describe experiments to show which surfaces absorb and emit most infrared radiation.	11.3			
Describe and explain some practical applications of thermal energy transfer.	11.4			

Chapter 12
Sound



IN THIS CHAPTER YOU WILL:

- describe how sounds are produced and how they travel
- measure the speed of sound
- describe how the amplitude and frequency of a sound wave are linked to its loudness and pitch
- state the range of human hearing
- define the term 'ultrasound' and describe some of its applications.

GETTING STARTED

Draw a table like this. Your table should fill a piece of A4 paper.

How are sounds made?	How does sound travel?	How fast is sound?
How do we detect sound?	How do sounds differ from each other?	Are there sounds we cannot hear?

Write or draw something in each cell of the table. Make it as detailed as you can.

Pair up with another student and compare your tables. Make any additions or changes you want to based on your discussion.

Join with another pair and share your ideas. Again, make any changes.

THE SOUND OF SILENCE

Figure 12.1: Outer space is a vacuum. This means sounds cannot travel through it. Astronauts communicate by using radio waves.

We are surrounded by sounds. Natural sounds include birds, animals and the wind. Other sounds include cars, computers and musical instruments. Sounds wake us, sounds alert us that our food is cooked, our plane is ready to board or that a car is approaching. It is hard for most of us to imagine a world without sound. How would we communicate our emotions? How would a baby attract attention when it is hungry? How different would our forms of entertainment be?

Our world is increasingly noisy as we add more machines and technology. Silence is not something city dwellers hear often. Psychologists believe noise is a major cause of stress. Acoustic engineers study ways to make a better sound environment. Mobile phone noise is alleviated by using vibration rather than sound to inform us of a call.

It is important for our wellbeing to reduce unnecessary noise, but sound reduction is not always entirely positive. Silent electric cars raise fears of more accidents as people are unaware of their approach.

In this chapter we will look at how sounds are created, how they travel and how we hear sounds. We will also look at why sounds can be so varied. Why are some sounds high or low pitched? Why are some sounds loud and others quiet?

Discussion questions

1. Evelyn Glennie (Figure 12.2) is one of the world's top percussionists despite being profoundly deaf. Can you work out how she experiences sound? (Hint: she plays barefoot.)

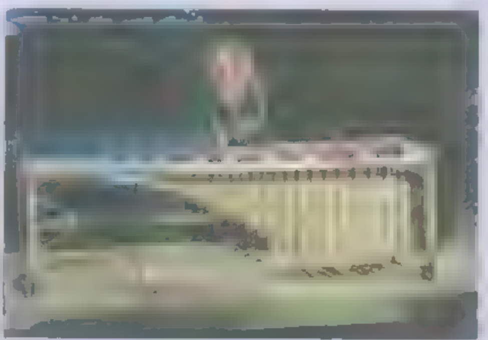


Figure 12.2: Some people are born or become deaf, or they are only able to hear a limited range of sound. They learn how to navigate the world using other senses.

2. Discuss with a partner all the ways in which you have used sound today. What adaptations could you make to get through your daily activities if you could not hear sounds?

12.1 Making sounds

All sounds are caused by something vibrating. The vibrations are not always visible because they may be too small or too fast. Vibrating sources cause the air around them to vibrate. These vibrations are passed through the air to our ears where they cause the eardrum to vibrate and we hear sound.

Figure 12.3: The water particles on this speaker are vibrating as the speaker makes a sound. The vibrations of the speaker and the water will change if the pitch or loudness of the sound is changed.

Figures 12.4–12.7 link sounds to the vibrating sources which cause them.

Figure 12.4: Hitting the tuning fork causes the prongs to vibrate.

Figure 12.5: Hitting the gong with a hammer causes it to vibrate.

Figure 12.6: The cicada has ribbed membranes at the base of its abdomen which vibrate causing a particularly loud sound.

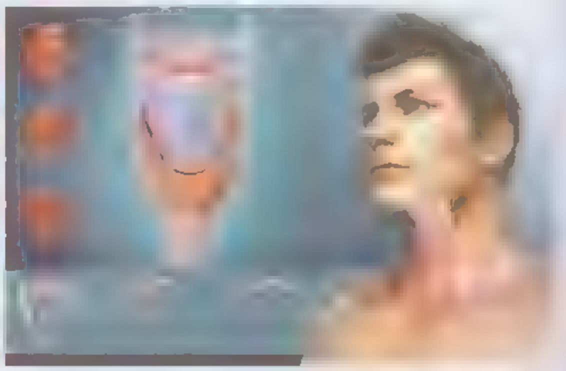


Figure 12.7: Vocal folds in the human throat vibrate to create speech.

Musical sounds

Musical instruments are engineered to vibrate in ways that make a range of interesting and beautiful sounds.

Figure 12.8: Djembe drums are made in a range of sizes to produce different notes. The skin vibrates when hit and produces sound waves.

String instruments are plucked or bowed to cause them to vibrate. The length of the string can be changed (usually by holding the string down with a finger) and this changes the note produced. The body of the instrument and the air inside it also vibrate and this gives the instrument its distinctive sound. This is why an oud and a violin can play the same note but sound very different.

Figure 12.9: The musician's left hand varies the length of the strings whilst his right plucks the strings to cause vibrations.

Wind instruments are blown to cause the column of air inside to vibrate. Players cover and uncover holes to change the length of the air column. This changes the pitch of the note.

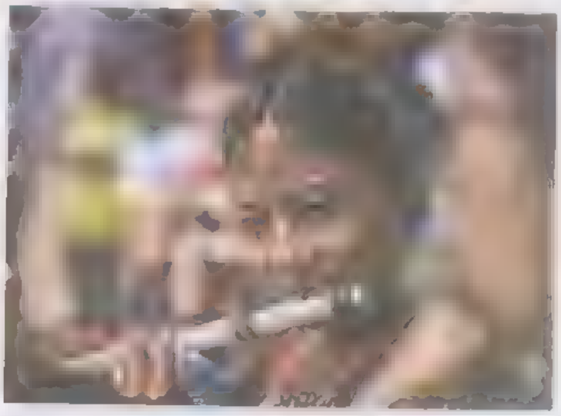


Figure 12.10: The system of holes on a flute allows a range of notes to be played.

An orchestra produces vibrations by a complex combination of hitting, plucking, bowing and blowing. These vibrations pass through the air to the audience, causing their eardrums to vibrate, so they hear the sound.

If the sound is very loud, such as at a rock concert, the audience may feel vibrations throughout their bodies and through the floor.

Questions

1. What are all sounds caused by?
2. A drum, a flute and a violin all play a note. For each instrument state what vibrates to create the sound.
3. Describe how a drummer hitting a drum leads to a listener hearing sound.

12.2 How does sound travel?

Sound is a series of vibrations passing through air or another material. The source of the sound vibrates and this makes the air particles around it vibrate back and forward in the direction the sound is travelling. These vibrations make a sound wave. This type of wave is called a longitudinal wave.

You will learn more about waves in Chapter 14.

The movement of the air particles can be demonstrated using a slinky spring, as shown in Figure 12.11.

Figure 12.11: Moving the end of the spring back and forwards causes the coils of the spring to be squashed together and then stretched out. The squashed up area moves along the spring but the spring remains in its original place

More about sound waves

When a tuning fork is hit, the prongs start to vibrate. Figure 12.12 shows how this creates a sound wave. As the right-hand prong moves forward, it squashes the air particles together. This makes a dense region in the air called a compression. As it moves back, the air particles are more spread out, making a less dense region called a rarefaction. Air does not move from the tuning fork to the listener – the vibrations pass through the air by the patterns of compressions and rarefactions caused by the air molecules being pushed back and forth.

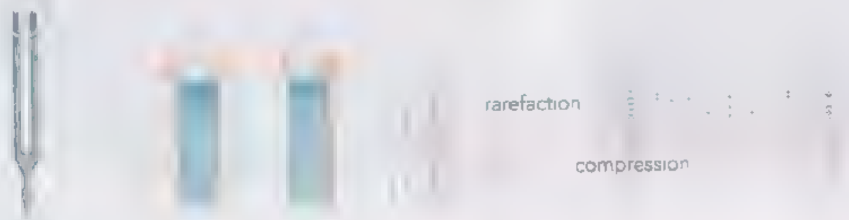


Figure 12.12: The tuning fork's prongs move back and forth creating compressions and rarefactions in the air

The vibrations of the prongs are not easy to see, but the effect on water can be dramatic, as seen in Figure

Figure 12.13: The number on the tuning fork tells us that the fork vibrates 440 times a second

compression a region of a sound wave where the particles are pushed together

rarefaction a region of a sound wave where the particles are further apart

What can sound travel through?

Sound waves are vibrations caused by particles moving back and forth. In a vacuum there are no particles, so it is impossible for sound to travel.

Sound needs a medium (material) to travel through. This can be shown using a bell in a glass jar. Figure 12.14 shows an experiment to demonstrate this.

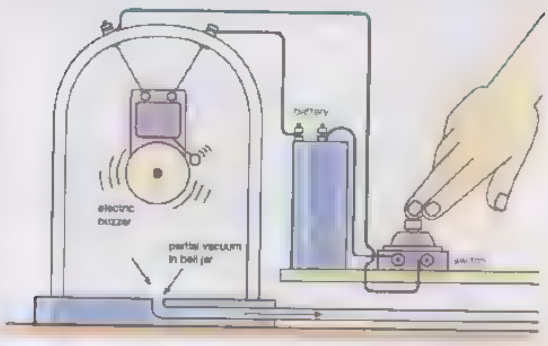


Figure 12.14: When the battery is connected, the bell can be seen and heard. Vibrations from the bell pass through the air in the jar, through the glass and then through the air to your ear. When the pump removes the air from the jar, the bell can still be seen vibrating, but cannot be heard.

Sound can travel through solids. You may be able to hear sounds from outside the classroom as you read this. Sound vibrations can travel through the walls.

Sounds can also pass through liquids. Many sea animals such as dolphins and whales use sound to communicate with each other and to navigate.

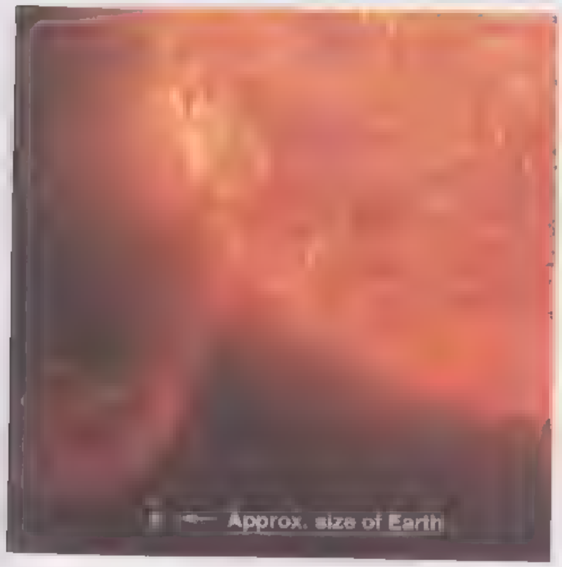


Figure 12.15: This is a solar flare, where a huge amount of matter is emitted by the Sun. An explosion like this on Earth would create a deafening sound.

The Sun is very active and yet we hear no sound from it. This is because there are no particles to carry the huge disturbances caused by explosions and solar flares. We can see the Sun because, unlike sound waves, light waves can travel through a vacuum.

Another major difference between sound and light waves is their speed. Light travels at 300 000 000 m/s, about a million times faster than sound. This means we see the lightning almost as it happens but hear the sound later. To calculate how many kilometres away the storm is, measure the time between the lightning and the thunder and divide by three. This works because sound travels 1 km in about 3 seconds.

Questions

4 Explain why sound cannot be heard in a vacuum.

5 Describe and explain what is heard when the vacuum pump in figure 12.14 is switched on.

6 A boy sees lightning and hears the thunderclap 9 seconds later. Calculate how far away is the storm is.

12.3 The speed of sound

Sound travels at between 330 m/s and 350 m/s in air. The speed changes slightly depending on the temperature and humidity of the air. This is much slower than light, but still so fast that we are usually not aware of the time it takes for sounds to reach us, unless the distance it travels is large.

An echo is a reflected sound wave. If you bang two wooden blocks together in the classroom you will hear only one bang. The sound will reflect from the walls, but the echo will be so close to the original bang that you will not hear it as a separate sound. Banging the blocks outside will mean the sound has further to travel so you may hear an echo. This can be used to measure the speed of sound.

EXPERIMENTAL SKILLS 12.1

Measuring the speed of sound in air

You can calculate the speed of sound in air by measuring the time taken for an echo to be heard

You will need
- 2 wooden blocks
- stopwatch
- long tape measure or trundle wheel

Safety: You will be creating very loud sounds. Avoid doing this near anyone's ears as loud sounds can damage the ear

Getting started

Why is it necessary to stand a long distance from the wall?

Why will it be difficult to measure the time from hitting the blocks together to hearing the echo?

Method

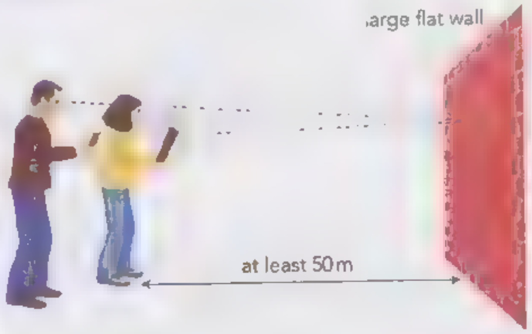


Figure 12.16: Measuring the speed of sound in air.

1. Stand a measured distance (ideally at least 50 metres) from a large flat wall. Bang the blocks together and listen for the echo.
2. Now try to bang the blocks in an even rhythm so that each clap coincides with the echo of the previous bang. This will mean you don't hear the echo separately from the next bang. This may take some practice.
3. Your partner should then measure the time for 20 of your bangs.
4. Record the time taken for 20 bangs and the distance from the wall.
5. Calculate the total distance travelled by the sound. Each bang involves the sound travelling to the wall and back, so the total distance is 20 × 2 × distance from wall.
6. Calculate the speed of sound in air. Use the equation:

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

Questions

1. What is the actual speed of sound in air? How does the value you calculated compare to this?
2. Which measurement (distance or time) do you think was least accurate? Explain your answer

Discuss the experiment with a partner. Suggest ways to improve your experiment to increase the accuracy of this measurement.

A more precise value of the speed of sound can be obtained using an electronic timer and microphones. Figure 12.17 shows this method. The wooden blocks and the two microphones are arranged in a straight line.

When the students bangs the two blocks of wood together, it creates a sudden, loud sound. The sound reaches microphone 1 and a pulse of electric current is sent to the timer. The timer starts timing. A fraction of a second later the sound reaches microphone 2.

A second pulse of current is sent to the timer and stops it. The timer now indicates the time it took for the sound to travel from microphone 1 to microphone 2. If the distance between the two microphones is measured, the speed of sound can be calculated using the equation:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

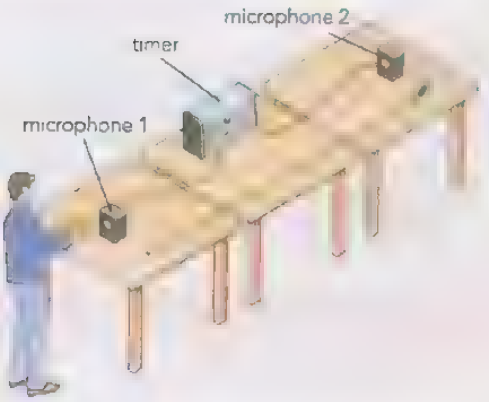


Figure 12.17: Another method for measuring the speed of sound.

A man blows a whistle and hears the echo from a rock face after 3.6 seconds. How far away from the rock is he? Assume speed of sound in air = 340 m/s.

Step 1: Calculate the distance travelled by the sound.

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

so, distance = speed × time

= 340 m/s × 3.6 s

= 1244 m

Step 2: Halve this distance. (The distance you have already calculated is the total distance travelled by the sound, to the rock face and back. The distance to the rock face is half of this.)

$$\frac{1224}{2} = 612\text{ m}$$

Answer

The rock face is 612 metres away from the man.

Sound travels at different speeds in different materials. Figure 12.18 shows the speed in different materials. This can be explained by considering the spacing of particles. Particles are closer together in solids than in liquids, so the vibrations can be passed on more easily in solids. This means that the sound wave travels faster in a solid.

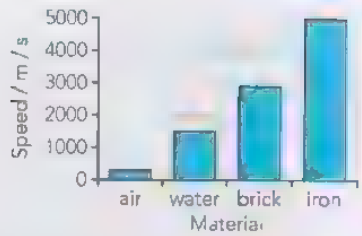


Figure 12.18: The speed of sound in different materials

Questions

7 A spectator at a cricket match sees the batsman hit the ball, then 1.2 seconds later he hears the stroke. How far away is the spectator? The speed of sound in air is 330 m/s.

8 Sound travels at 1500 m/s in fresh water and at 1530 m/s in salt water. Explain the difference in speeds.

9 Explain why the method shown in Figure 12.17 is more accurate than the echo method when measuring the speed of sound.

12.4 Seeing and hearing sounds

Seeing sounds

A cathode ray oscilloscope and microphone can be used to represent sounds on a display screen (Figure 12.19). The microphone picks up the sound and converts it to an electrical signal. The oscilloscope converts this to a line which represents the vibrations that make up the sound wave.

The vibration from a musical instrument is complicated because it is produced by vibrations of the air and the instrument itself. A signal generator can be used to produce a pure sound wave. Pure notes are easier to measure, but not so musical.

The oscilloscope trace that represents a pure note is a simple curve as shown in Figure 12.20a. When representing a musical note from a particular musical instrument, the pattern is more complicated. Figures 12.20b and c show this.

Figure 12.19: As the student blows, he creates vibrations in the air The vibrations are detected by the microphone and converted to e ectrical signals, which are displayed on the oscilloscope.

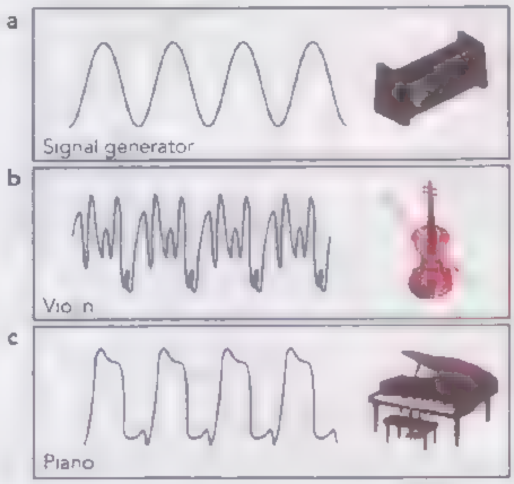


Figure 12.20: The three representations of sound waves shown here are all the same note Each wave has a repeating pattern The design of the instrument adds extra vibrations called overtones which give each nstrument its dist nctive sound. A l three waves have four repeats, meaning that they all are the same note

The oscilloscope can be used to observe two important things about the wave (Figure 12.21).

- The amplitude is the furthest distance the particles move from their undisturbed position. This is shown by the height or depth of the oscilloscope trace.
- The frequency is the number of vibrations each second. The more waves on the screen, the higher the frequency. Frequency is measured in hertz. One hertz means one wave per second.

amplitude the greatest height or depth of a wave from its undisturbed position

frequency. the number of complete vibrations or waves per unit time

hertz: the un't of frequency; 1 Hz = 1 wave per second

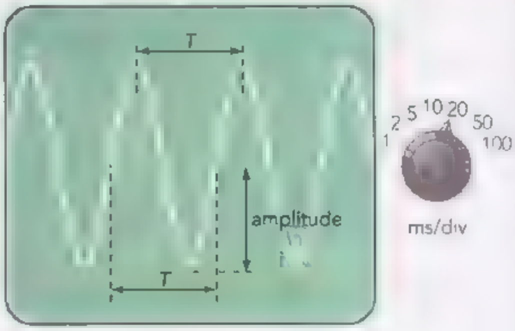


Figure 12.21: The frequency of the note can be calculated from the osc'lloscope trace. This oscil oscope is set at 20 ms/div. This means each division on the grid represents 20 ms (0.02 s). The time for one wave (marked as T) is two divisions or 0.04 seconds One wave takes 0.04 seconds, so the number of waves each second is $1 \div 0.04 = 25$ Hz

Connecting a signal generator and a speaker to an oscilloscope allows you to both see a representation of the sound wave and hear the sound.

Increasing the loudness of the sound produces taller waves – they have a bigger amplitude. Increasing the frequency means more waves will be seen on the screen – they have a higher frequency, and the sound heard will be higher pitched. Remember:

- high frequency means high pitch
- large amplitude means loud sound.

Hearing sounds

Young humans can hear sounds from 20 Hz up to 20 000 Hz. As we grow older, the sensory cells in the ear which detect vibrations deteriorate. This means that the range of sounds which can be heard decreases with age. These cells can also be damaged by repeated exposure to very loud noise.

Sounds which have a higher frequency than 20 000 Hz are too high pitched to be heard by the human ear. These sounds are known as **ultrasound**.

ultrasound: any sound with a frequency higher than 20 000 Hz

Figure 12.22: This whistle was invented by a scientist called Francis Galton in around 1900 to help him investigate human hearing. Similar whistles are used in animal training.

Many animals can hear high pitched sounds that we cannot. Many animals such as dolphins communicate using ultrasound. Whistles creating ultrasound can be used to train animals (Figure 12.22)

An annoying noise

The mosquito sound alarm is a device intended to stop young people congregating in areas where they are not wanted. The device emits a high pitched pulsing sound which young people can hear but older people cannot. It is not harmful but is annoying to those who can hear it.

Prepare a leaflet to inform young people about the device and the science behind it. Use the words 'frequency' and 'ultrasound' in your explanation.

Swap leaflets with another student. Complete a grid like this to give them feedback:

Question	🙂😐🙁	Comments
Does the leaflet explain what the frequency of a sound is?		
Does it explain the difference in hearing range between teenagers and adults?		
Does it explain why the mosquito device will stop young people hanging around where they are not wanted?		

Applications of ultrasound

Sonar

Sonar is a method used to measure the depth of water or to locate an underwater object. Figure 12.23 shows how this works.

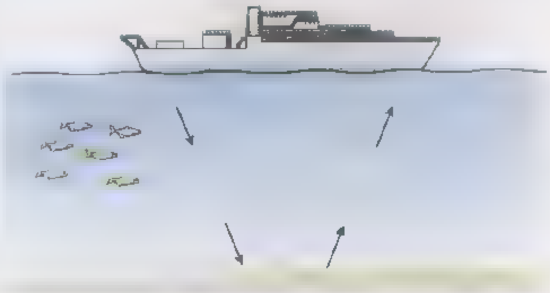


Figure 12.23: Using sonar to measure depth. What effect might the fish have?

A pulse of ultrasound is sent down from a boat and reflects from the seabed. The time taken for the reflected pulse to be received is measured. This is used, with the speed of sound in water, to calculate the depth of the water.

A ship sends out an ultrasound pulse and receives the echo after 3 seconds. The speed of sound in water is 1500 m/s. Calculate the depth of the water.

Step 1: Calculate the distance travelled by the pulse.

distance = speed × time = 1500 m/s × 3 s
= 4500 m

Step 2: Halve this to get the depth. Remember the pulse goes down and back up again.

depth = $\frac{4500\text{ m}}{2}$ = 2250 m

Answer

The depth of the water is 2250 m.

Material testing

Ultrasound can be used to detect flaws inside materials. A small crack in a metal girder could cause a building to collapse. Figure 12.24 shows ultrasound being passed through uncracked (A) and cracked (B) metal. The original and reflected pulses are shown on oscilloscope trace A. Oscilloscope trace B has an extra peak. This indicates to the engineers that some ultrasound is being reflected from a crack or flaw inside the metal.

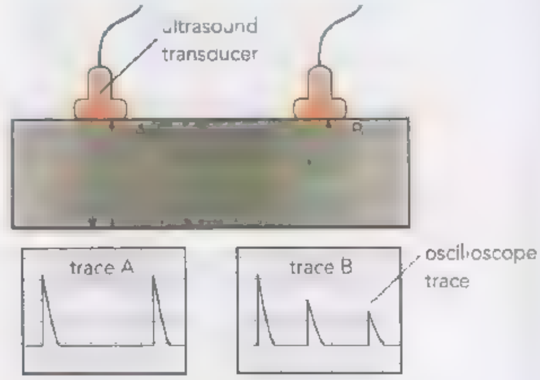


Figure 12.24: The exact location of the flaw can be calculated from the speed of sound in the metal and the time for the reflected pulse to be detected.

Ultrasound is also used in medicine (Figure 12.25). Ultrasonic waves are partially reflected from boundaries between different materials, such as the chambers of a patient's heart, or a fetus. Computer analysis of the reflected waves produces an image.

Figure 12.25: The ultrasound image shows the doctor and the mother how this fetus is developing.

Questions

10 State the range of sound a young person can typically hear.

11 Describe what happens to this range as the person gets older. What else can have this effect on hearing?

12 Figure 12.26 shows the traces produced on an oscilloscope by three different sounds.

Figure 12.26: Three sounds produced on an oscilloscope

a Which sound is quietest? Explain your answer.

b Which two sounds have the same pitch? Explain your answer.

13 A ship positioned above a shoal of fish (Figure 12.27) sends out an ultrasound pulse and receives two reflected pulses, one after 0.2 seconds and the other after 0.5 seconds. The speed of sound in water is [illegible]500 m/s.

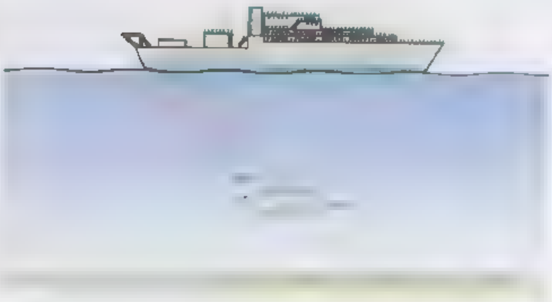


Figure 12.27: Using ultrasound to find depth

a Calculate the depth of the sea.

b Calculate the depth of the shoal of fish.

c Explain why the [illegible]flected pulse lasts for longer than the [illegible]

PROJECT

How do musical instruments produce a range of notes?

Your task is to investigate how different instruments create a range of sounds.

Wind instruments

Wind instruments produce sounds by making columns of air vibrate. Putting different amounts of air into test tubes creates columns of air above the water. The air can be made to vibrate by tapping the glass or by blowing over the top of the tube.

Investigate the effect of changing the length of the air column. How does it affect the pitch of the note produced?

Plucked instruments

Plucking a stretched string creates a sound. Use a stringed instrument or a homemade elastic band guitar to investigate the relationship between the length of the string and the pitch of the sound.

Optional

Extend your investigation to answer one of the following.

- What other methods are used to produce different notes in musical instruments?
- Is the note produced by a string affected by other factors such as the material it is made from, its thickness or the tension (how tightly it is stretched)?
- How is the frequency of a note from a string related to length? You can measure the frequency of the sound directly or by using a microphone and oscilloscope. You can draw a graph of frequency against length.

Present your results to the class. This could be as a poster, a talk, a presentation, or playing a recognisable tune on an improvised instrument. You should include evidence such as diagrams, tables or graphs.

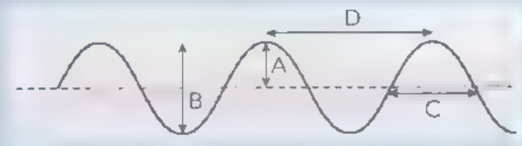
Figure 12.28: A musical instrument that is plucked

SUMMARY

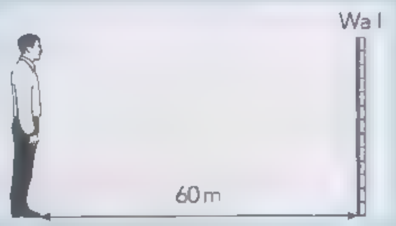
All sounds are caused by vibrating sources.
Sound waves are longitudinal waves.
Sound waves consist of a series of compressions and rarefactions.
Sound waves need a medium to travel through.
Sound travels at between 330 m/s and 350 m/s in air.
Sound travels fastest in solids and slowest in gases.
An echo is a reflected sound
The greater the amplitude of a sound, the louder the sound.
The greater the frequency of a sound, the higher its pitch.
Humans can hear sounds between 20 Hz and 20 000 Hz.
Ultrasound can be used in medical scans, testing materials and depth calculation.

EXAM-STYLE QUESTIONS

1 **Which arrow shows the amplitude of the sound wave?** **[1]**



2 **A student stands 60 metres from a wall. He makes a sound and hears the echo 0.3 seconds later.**



Which is the correct calculation to help him find the speed of sound? **[1]**

A 60 ÷ 0.3 **B** 120 ÷ 0.3 **C** 120 ÷ 0.6 **D** 60 × 0.3

3 **What is the typical range of sound a human ear can detect?** **[1]**

A 200–20 000 Hz **C** 200–2000 Hz

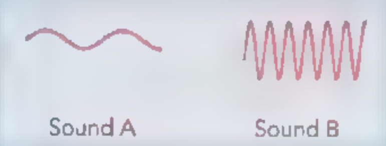
B 20–2000 Hz **D** 20–20 000 Hz

4 a What is meant by the term 'frequency of a sound'? [1]

b What units is frequency measured in? [1]

c What name is given to sounds with a frequency of more than 20 000 Hz? [1]

d The diagram shows the traces produced on an oscilloscope by two different sounds. **Describe** **two** ways in which sound B is different from sound A. [2]



[Total: 5]

5 A drummer is playing a solo.

a Describe how the sound produced travels through the air. [1]

b What type of wave is a sound wave? [1]

c Describe an experiment to show that sound needs a medium to travel through. [2]

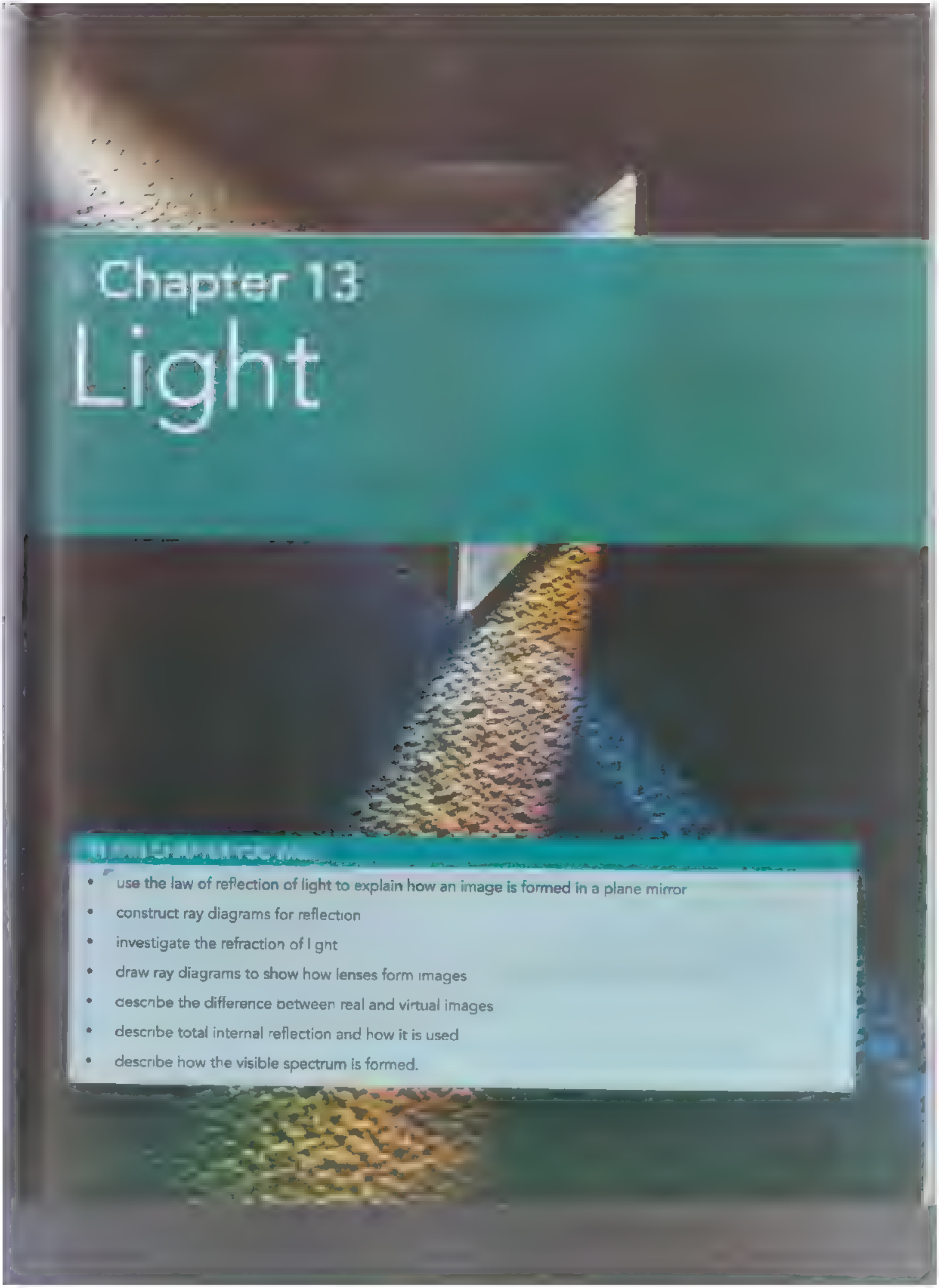
[Total: 4]

describe: state the points of a topic; give characteristics and main features

calculate: work out from given facts, figures or information

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively

Describe how sounds are produced	12.1			
Describe sound waves.	12.1			
Use the terms 'compression' and 'rarefaction'.	12.2			
State that sound needs a medium.	12.2			
State the speed of sound in air	12.3			
Describe a method to measure the speed of sound in air.	12.3			
Compare the speed of sound in solids, liquids and gases.	12.3			
Describe how the amplitude of a sound affects its loudness.	12.4			
Describe how the frequency of a sound affects its pitch	12.4			
Explain how an echo is made	12.3			
Define the term 'ultrasound'	12.4			
State the range of sounds which humans can hear.	12.4			
Describe medical and engineering applications of ultrasound.	12.4			



Chapter 13

Light

[illegible]

- use the law of reflection of light to explain how an image is formed in a plane mirror
- construct ray diagrams for reflection
- investigate the refraction of light
- draw ray diagrams to show how lenses form images
- describe the difference between real and virtual images
- describe total internal reflection and how it is used
- describe how the visible spectrum is formed.

GETTING STARTED

The statements opposite are all true, but there are some exceptions to each statement. Discuss each statement and identify when light behaves differently. Rewrite each statement to include these exceptions.

- *Light travels in straight lines.*
- *Light passes straight through glass.*
- *Light always travels at the same speed.*

THE WORLD IN A DROP OF RAIN

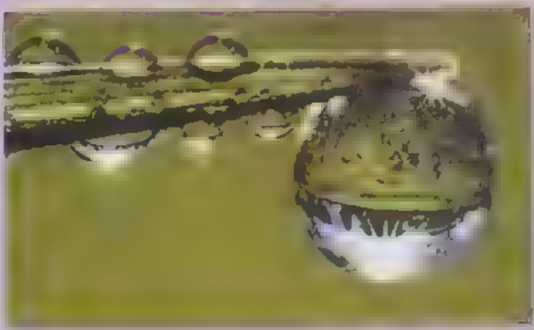


Figure 13.1: The light is bent by the raindrop, forming an upside down image of the scene

This raindrop on a blade of glass shows an image of its surroundings. The light rays causing this have travelled about 150 million kilometres from the Sun to the Earth. Some rays striking the grass are absorbed and supply energy for photosynthesis, while others are reflected, allowing you to see the grass. Those rays passing through the water drop are refracted (bent) to form the image that you see.

Notice that the Sun is at the bottom and the trees appear to grow downwards. The image is upside down. Your eyes contain lenses which produce images in a very similar way to the water drop. Light from the Sun reflects from different objects and enters your eyes. The lens forms an upside-down image, like the water drop. Your brain knows the image is upside down so automatically turns it upright. It has had years of practice, so you are not aware of this process.

The image in Figure 13.1 has been captured using a camera which also contains a lens to produce an image.

Light travels at 300 million metres per second, so it takes eight minutes and 20 seconds to travel from the Sun to the Earth. This means that if the Sun stopped producing light, we would not know for eight minutes and 20 seconds.

In this chapter you will learn more about the processes of reflection and refraction, which can help us explain how light behaves.

When Apollo astronauts visited the Moon, they left behind reflectors on its surface. These are used to measure the distance from the Earth to the Moon. A laser beam is directed from an observatory on Earth so that it reflects back from these reflectors left on the lunar surface. The time taken by the light to travel there and back is measured and, because the speed of light is known, the distance can be calculated.

A similar method can be used with sound waves to measure the depth of water. Sound is reflected from the sea bed and the time taken is measured. Knowing the speed of sound in water allows the depth to be calculated.

Discussion questions

1. How are these two methods similar?
2. What are the differences?
3. Why is light suitable for one and sound for the other?

13.1 Reflection of light

Light usually travels in straight lines. It changes direction if it hits a shiny surface. This change in direction at a shiny surface such as a mirror is called **reflection**. We will look at reflection in this section.

You can see that light travels in a straight line using a **ray box**, as shown in Figure 13.2. A light bulb produces light, which spreads out in all directions. A ray box produces a broad beam. By placing a narrow slit in the path of the beam, you can see a single narrow beam or **ray** of light. The ray shines across a piece of paper. You can record its position by making dots along its length. Laying a ruler along the dots shows that they lie in a straight line.

Figure 13.2a: A ray box produces a broad beam of light, which can be narrowed down using a metal plate with a slit in it. **b:** Marking the line of the ray with crosses allows you to record its position.

You may see demonstrations using a different source of light, a **laser**. A laser (Figure 13.3a) has the great advantage that all of the light it produces comes out in a narrow beam. All of the energy is concentrated in this beam, rather than spreading out in all directions (as with a light bulb). The total amount of energy coming from the laser is probably much less than that from a bulb, but it is much more concentrated. That is why it is dangerous if a laser beam gets into your eye.

reflection: the change of direction of a ray when it strikes a surface without passing through it

ray box: apparatus used to produce a ray of light

ray: a narrow beam of light

laser: a device for producing a narrow beam of light of a single colour (monochromatic) or wavelength

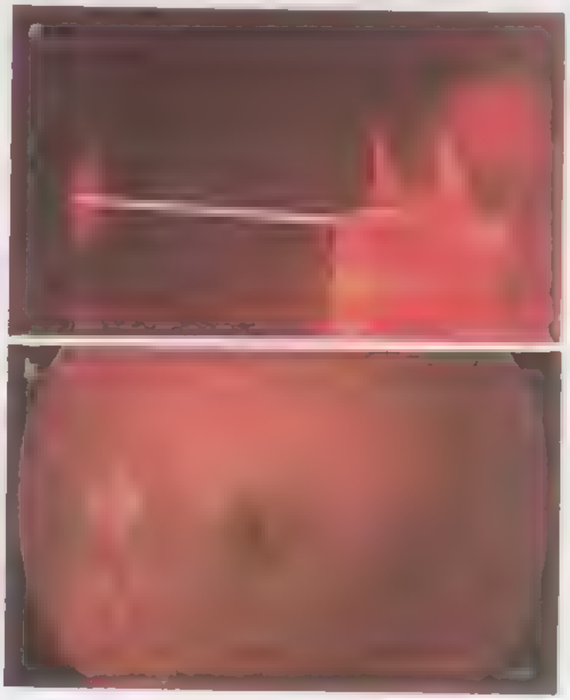


Figure 13.3a: Laser beams are very intense. It is important to protect your eyes when using a laser. **b:** Scarring (just left of centre) to the retina of a child after looking at a laser pointer.

Looking in the mirror

Most of us look in a mirror, at least once a day, to check on our appearance (Figure 13.4). It is important to us to know how people see us.

Archaeologists have found bronze mirrors more than 2000 years old, so the desire to see ourselves clearly has been around for a long time.

Figure 13.4: Psychologists use mirrors to test the intelligence of animals. Do they recognise that they are looking at themselves? Chimpanzees' reactions show they clearly do recognise their images. Other animals, such as cats and dogs, do not – they may even try to attack their own reflection.

Modern mirrors give a very clear image. When you look in a mirror, rays of light from your face reflect off the shiny surface and back to your eyes. You seem to see an image of yourself behind the mirror. To understand why this is, we need to use the law of reflection of light.

When a ray of light reflects off a mirror or other reflecting surface, it follows a path as shown in Figure 13.5. The ray bounces off, rather like a ball bouncing off a wall. The two rays are known as the **incident ray** and the **reflected ray**.

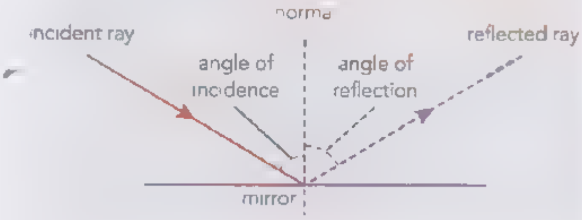


Figure 13.5: This **ray diagram** shows the reflection of light. The normal is drawn at 90° to the mirror. Then the angles are measured between the rays and the normal. The angle of incidence and the angle of reflection are equal: $i = r$

The **angle of incidence**, i, and the **angle of reflection**, r, are found to be equal to each other. This is the law of reflection.

angle of incidence = angle of reflection

$i = r$

Angles of incidence and reflection are always measured between the ray and the **normal** to the surface. The angles between the rays and the mirror are also equal, but it would be hard to measure them if the mirror was curved. The law of reflection also works for curved mirrors.

KEY WORDS

incident ray: a ray of light arriving at a surface

reflected ray: a ray of light which has been reflected from a surface

ray diagram: a diagram showing the path of rays of light

angle of incidence: the angle between the incident ray and the normal drawn at the point where the ray hits the surface

angle of reflection: the angle between the reflected ray and the normal drawn at the point where the ray hits the surface

normal: the line drawn at right angles to a surface at the point where a ray hits the surface

ACTIVITY 13.1

Investigating the law of reflection

Figure 13.6: Investigating the law of reflection

The student in Figure 13.6 is investigating the law of reflection.

Write step-by-step instructions for his investigation. Include a list of the apparatus needed, and the measurements that he should take.

The image in a plane mirror

Why do we see such a clear image when we look in a plane mirror? And why does it appear to be behind the mirror?

a

b

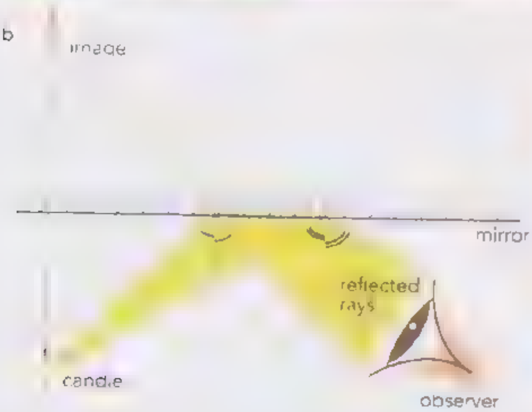


Figure 13.7a: Looking in the mirror, the observer sees an image of the candle. The image appears to be behind the mirror. **b:** The ray diagram shows how the image is formed. Rays from the candle flame are reflected according to the law of reflection.

Figure 13.7a shows how an observer sees an image of a candle in a plane mirror. Light rays from the flame are reflected by the mirror . Some of them enter the observer's eye. The observer has to look forward and slightly to the left to see the image of the candle

Figure 13.7b shows how the image is formed. The solid lines show the light from the candle reflecting from the mirror. The girl's brain assumes that the rays have travelled in straight lines from a point behind the mirror. shown by the dashed lines. (Our brains assume that light travels in straight lines, even though we know that light is reflected by mirrors.) In reality, no light is coming from behind the mirror. The dashed lines appear to be coming from a point behind the mirror, at the same distance behind the mirror as the candle is in front of it. You can see this from the symmetry of the diagram.

The image looks as though it is the same size as the candle. Also, it is (of course) a mirror image – it is left–right reversed, or laterally inverted. You will know this if you have seen writing reflected in a mirror. If you could place the object and its image side-by-side, you would see that they are mirror images of each other, in the same way that your left and right hands are mirror images of each other

The image of the candle in the mirror is not a real image. A real image is an image that can be formed on a screen. If you place a piece of paper at the position of the image, you will not see a picture of the candle on it, because no rays of light from the candle reach that spot. That is why we drew dashed lines, to show where the rays appear to be coming from. We say that it is a virtual image.

Key words

image: what we see when we view an object by means of reflected rays

plane mirror: (or a flat mirror) a mirror with a flat, reflective surface

laterally inverted: an image in which left and right have been reversed

real image: an image that can be formed on a screen

virtual image: an image that cannot be formed on a screen

To summarise, when an object is reflected in a plane mirror, its image is:

- the same size as the object
- the same distance behind the mirror as the object is in front of it
- laterally inverted
- virtual.

Questions

1 a Why is the word ambulance written in reverse on the front of this vehicle?

Figure 13.8: An ambulance.

b Write the word POLICE in the same way.

2 A student investigated the law of reflection. She increased her angle of incidence by 20° each time.

Angle of incidence	Angle of reflection
20°	20°
40°	39°
60°	30°

a Which angle of reflection did she measure incorrectly?

b Suggest what she may have done wrong.

3 Draw a diagram to show a ray hitting a mirror with an angle of incidence of 40°. Draw the reflected ray. Label both rays, the normal and the angles of incidence and reflection.

4 What angle must ray hit a mirror at for the direction of the ray to be turned through 90°? Draw a diagram to illustrate your answer.

Ray diagrams

Light rays follow strict rules. By following the same rules we can construct detailed ray diagrams. These show where an image is formed and what type of image it is. Worked Example 13.1 shows the steps in constructing a ray diagram to show the formation of an image in a plane mirror.

[illegible]

A small lamp is placed 5 cm in front of a plane mirror. Draw an accurate scale diagram, and use it to show that the image of the lamp is 5 cm behind the mirror.

The steps needed to draw the ray diagram are listed below and shown in Figures 13.9a–d. (It helps to work on squared paper or graph paper.)

Step 1: Draw a line to represent the mirror. Indicate its reflecting surface by drawing short lines on the back of the line. Mark the position of the object (the lamp) with a cross and label it O.

Figure 13.9a

CONTINUED

Step 2: Draw two rays from the object to the mirror. Draw in the normal lines where they strike the mirror.

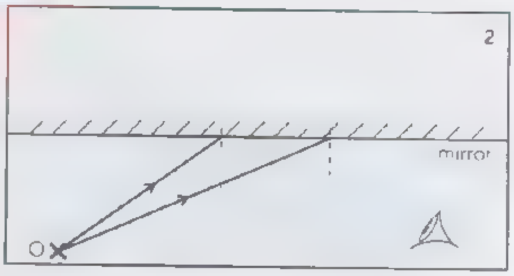


Figure 13.9b

Step 3: Using a protractor, measure the angle of incidence for each ray. Mark the equal angle of reflection. Draw in the reflected rays.

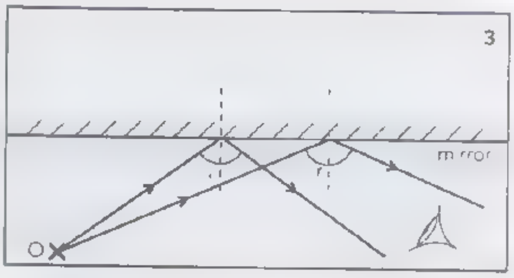


Figure 13.9c

Step 4: Extend the reflected rays back behind the mirror. Draw this using dotted lines. The point where they cross is where the image is formed. Label this point I.

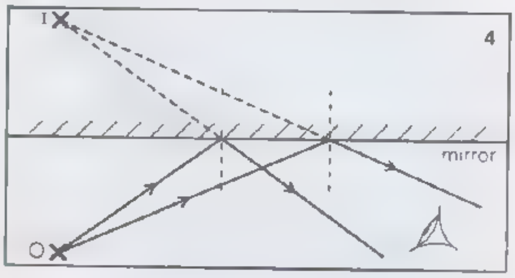


Figure 13.9d

Answer

From the diagram for Step 4, it is clear that the image is 5 cm from the mirror, directly opposite the object. The line joining O to I is perpendicular to the mirror.

Questions

5 Figure 13.10 shows an object placed 6 cm from a plane mirror.

Figure 13.10: Object and mirror

a Copy Figure 13.10 and use the law of reflection to find the path of the rays after they hit the mirror.

b Trace these rays back to find the position of the image.

c Measure the perpendicular distance from the image to the mirror.

6 Figure 13.11 shows how a periscope uses mirrors to allow the user to see beyond obstacles.

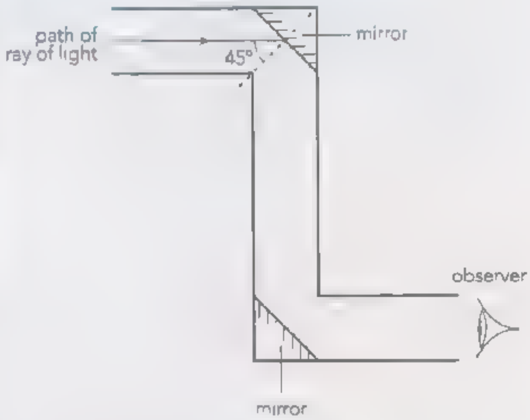


Figure 13.11: Periscope.

a Copy and complete the diagram in Figure 13.11 to show how the light reaches the observer.

b The image the observer sees is not laterally inverted. Explain why.

13.2 Refraction of light

Figure 13.12: The ripples seen on the bottom of the pool are caused by water bending the light.

If you look down at the bottom of a swimming pool, you may see patterns of shadowy ripples as in Figure 13.12. The surface of the water is not flat. There are often small ripples on the water, and these cause the rays of sunlight to change direction. Where the pattern is darker, rays of light have been bent away, producing a sort of shadow. This bending of rays of light when they travel from one medium to another is called **refraction**.

There are many effects caused by the refraction of light. Some examples are the sparkling of diamonds, the way the lens in your eye produces an image of the world around you, and the twinkling of the stars in the night sky. The image of a bent straw in liquid (Figure 13.13) is another consequence of refraction.

Figure 13.13: The straw is partly immersed in the drink. Because of the refraction of the light coming from the part of the straw that is underwater, the straw appears bent.

Refraction occurs when a ray of light travels from one medium into another. The ray of light may change direction. Refraction happens at the boundary between the two materials. The ray approaching the boundary is called the incident ray and the ray leaving the boundary is called the refracted ray. The angle of incidence, *i*, and **angle of refraction**, *r*, are measured to the normal drawn at the point where the ray hits the boundary (see Figure 13.14).

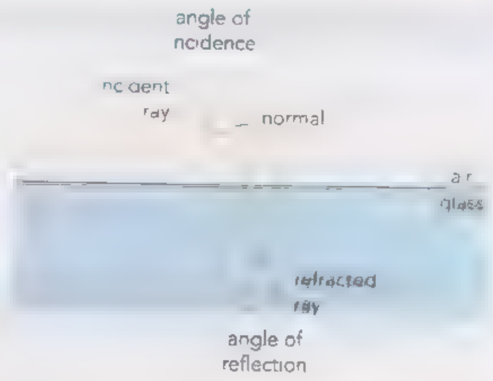


Figure 13.14: Refraction of a light ray entering glass

KEY WORDS

refraction: the bending of light when it passes from one medium to another

angle of refraction: the angle between a refracted ray and the normal to the surface at the point where it passes from one medium to another

EXPERIMENTAL SKILLS 13.1

Investigating refraction

You can investigate refraction by shining a ray of light into a glass or Perspex® block and tracing the path of the ray.

You will need:

- ray box
- power pack
- rectangular glass or Perspex® block
- glass or Perspex® of different shapes
- plain paper
- optical pins.

Safety: You will be working in a darkened area, so keep your work area tidy to avoid trip hazards.

Getting started

How will you mark the path of the rays going in and out of the block?

How will you determine the path of the ray inside the glass block?

Method

1. Place the block on paper and draw round it.
2. Shine a ray into the block as shown in Figure 13.15. Look carefully at the ray inside the glass. You will see it travels in a straight line. It only bends at the surface.

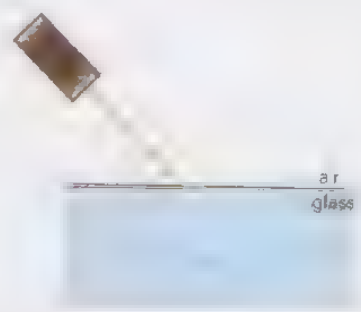


Figure 13.15: Ray hitting the glass block.

3. Mark the ray going into the block and the ray coming out of the block with crosses or optical pins.
4. Remove the block and draw the ray going in to the block and the ray coming out.

CONTINUED

5 Join these two rays to show the path of the light through the glass.

6 Draw the normal at the points where the ray enters and leaves the block.

7 Measure angles *i* and *r* for the ray entering the block and record them in a table.

Angle of incidence in air, *i*	Angle of refraction in glass, *r*

8 Repeat this for rays entering the block at different angles.

9 If you have blocks of different materials, repeat the experiment to find out which material bends light the most.

10 Investigate what happens if a ray of light hits the glass block at 90°.

11 Investigate the refraction of light as it passes through different shaped blocks, such as those in Figure 13.16.

12 Record your observations in sketches. Note any unexpected effects you observe – these will be explained later in this chapter.

Figure 13.16: Light rays incident on glass blocks

Questions

1 Copy and complete these sentences:

When a ray goes from air to glass it bends ______ the normal.

For a ray going from air to glass, the angle of ______ is smaller than the angle of ______.

When a ray goes from glass to air it bends ______ the normal.

2 Describe what happens when a ray hits the block at 90°.

Changing direction

Figure 13.17 shows light passing through a rectangular block. Notice that the light only bends at the point where it enters or leaves the block, so it is the change of material that causes the bending.

From Figure 13.17, you can see that the direction in which the ray bends depends on whether it is entering or leaving the glass.

- The ray bends towards the normal when entering the glass.
- The ray bends away from the normal when leaving the glass.

One consequence of this is that, when a ray passes through a parallel-sided block of glass or Perspex®, it returns to its original direction of travel, although it is shifted to one side.

Figure 13.17: Demonstrating the refraction of a ray of light when it passes through a rectangular block of glass or Perspex®. The ray bends as it enters the block. As it leaves it bends back to its original direction.

When we look at the world through a window, we are looking through a parallel-sided sheet of glass. Although the rays of light are shifted slightly as they pass through the glass, we do not see a distorted image because they all reach us travelling in their original direction

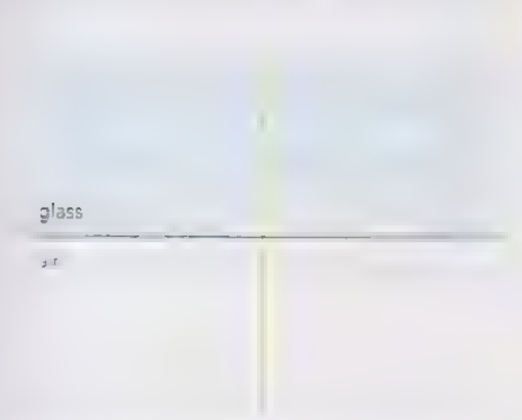


Figure 13.18: When a ray hits a boundary at 90° it is not refracted

A ray of light may strike a surface at an angle of incidence of 0°, as shown in Figure 13.18. In this case, it does not bend — it simply passes straight through and carries on in the same direction. Usually we say that refraction is the bending of light when it passes from one medium to another. However, we should bear in mind that, when the light is perpendicular to the boundary between the two materials, there is no bending.

Explaining refraction

Light is refracted because it travels at different speeds in different materials. Light travels fastest in a vacuum (empty space) and almost as fast in air. It travels more slowly in glass, water and other transparent substances.

Figure 13.19 shows how a change of speed can cause a change of direction. Imagine a truck is driving along a road across the desert. The driver is careless and allows the wheels on the left to drift off the road onto the sand. Here, they spin around, so that the left-hand side of the truck moves more slowly. The right-hand side is still on the road, and keeps moving quickly, so that the truck starts to turn to the left.

The boundary between the two materials is the edge of the road. The normal is at right angles to the road. The truck has turned to the left, so its direction has moved towards the normal.

This matches what we have seen with light. Light slows down when it goes from air to glass, and it bends towards the normal (Figure 13.14)

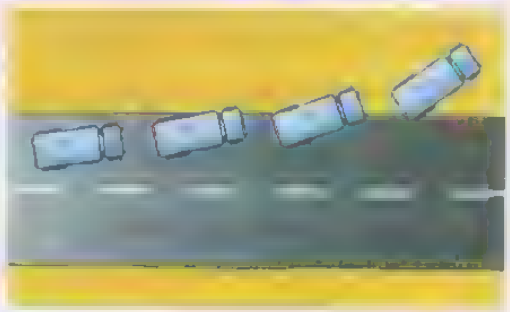


Figure 13.19: To explain why a change in speed explains the bending caused by refraction, picture a truck's wheels slipping off the road into the sand. The truck turns to the side because it cannot move so quickly through the sand

Questions

7 Describe what happens to a ray of light that passes from:

  a air to glass

  b glass to air.

8 Why are the angle of incidence and the angle of refraction always measured between the ray and the normal?

9 Draw a diagram to show a light ray passing from glass to air. Mark the incident and refracted rays, the normal and the angles of incidence and refraction.

10 A swimming pool is lit from the bottom.

Use Figure 13.20 to explain why the swimming pool appears to be shallower than it is.

Figure 13.20: Light in a swimming pool

Refractive index

Light travels very fast. As far as we know, nothing can travel any faster than light. The **speed of light** as it travels though empty space is exactly 299 792 458 m/s. This is usually rounded to 300 000 000 m/s or 3×10^8 m/s.

When a ray of light passes from air into glass, it slows down and bends towards the normal. This happens when light passes from one transparent medium to another, or when light passes between different regions, such as from hot water to cold water.

The **refractive index** of a material is a measure of how much the light slows, or how much it is bent. If the speed of light is halved when it enters a material, the refractive index is 2, and so on. The refractive index is the ratio of the speeds of light in two different media or different regions.

KEY WORDS

speed of light: the speed at which light travels (usually in a vacuum: 3.0×10^8 m/s)

refractive index: the ratio of the speeds of a light wave in two different media

Material	Speed of light / m/s	$\frac{\text{speed in vacuum}}{\text{speed in material}}$
vacuum	2.998×10^8	1 exactly
air	2.997×10^8	1.0003
water	2.308×10^8	1.33
Perspex®	2.000×10^8	1.5
glass	$(1.800–2.000) \times 10^8$	1.5–1.7
diamond	1.250×10^8	2.4

Table 13.1: The speed of light in some transparent materials. Note that the values are only approximate.

Calculating refractive index

ACTIVITY 13.2

Interpreting data

You can use the measurements you took in Experimental skills 13.1 to investigate the relationship between the angles of incidence and refraction.

CONTINUED

Angle of incidence, i	Angle of refraction, r	$\sin i$	$\sin r$	$\frac{\sin i}{\sin r}$

Use a calculator or tables to find the sine of each angle, and divide $\sin i$ by $\sin r$.

If you investigated different blocks, draw and complete a table for each.

Question

1 What can you conclude about the value of $\frac{\sin i}{\sin r}$?

material. This value is the refractive index of the material. The refractive index of glass is about 1.5 and the refractive index of water is about 1.33.

Refractive index (n) can be calculated using the equation

$$\frac{\sin i}{\sin r}$$

Refractive index:

$$n = \frac{\sin i}{\sin r}$$

WORKED EXAMPLE

A ray of light hits the surface of water at an angle of incidence of 30°. It is refracted at an angle of 22°. Find the refractive index, n, of water.

Step 1: Write down what you know and what you want to find out.

Step 2: Write down the equation and substitute these values.

CONTINUED

Step 3: Use a calculator or tables to find the sines and

$$n = \frac{0.5}{0.375}$$

Answer

$n = 1.33$

Questions

11 A ray of light enters a block of glass at an angle of incidence of 40°. The angle of refraction in the glass is 25°. Calculate the refractive index of the glass.

12 a Define 'refractive index'.

b Explain why refractive index does not have a unit.

13 a Describe what happens to the speed of light as it passes from air to glass.

b Use your answer to part **a** to explain why light entering glass at an angle is refracted.

c Explain in terms of the speed of light why a ray entering the glass along the normal is not refracted.

14 Figure 13.21 shows a ray of light passing from air into an unknown material (X). The ray is deflected by 19°.

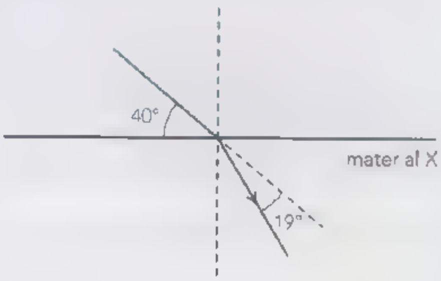


Figure 13.21: Ray of light passing into a material.

a Determine the angles of incidence and refraction.

b Calculate the refractive index of material X. Give your answer to two significant figures.

15 a Refraction can happen when light passes from one transparent solid to another. Use the information in Table 13.1 to deduce what will happen to a ray of light passing from diamond to glass. Sketch a diagram to show what will happen.

16 A ray of light enters glass with a refractive index of 1.52 at an angle of incidence of 60°.

a Calculate the angle of refraction.

b Calculate the speed of light in the glass.

13.3 Total internal reflection

When you investigated refraction you may have noticed that not all the light is refracted. Some is reflected back from the surface, as shown in Figure 13.17. You can also see that as the light emerges from the glass, some light is reflected back inside the glass. This is called **internal reflection**.

Like all reflected light, these reflected rays obey the law of reflection:

angle of incidence = angle of reflection

Rays reflected back inside materials such as glass can be very useful. Figure 13.22 shows internal reflection. A ray of light is incident on a semicircular glass block. The ray enters the curved side of the block at right angles and so passes straight through to the midpoint of the straight side.

Figure 13.22: Using a ray box to investigate reflection when a ray of light strikes a glass block. The ray enters the block without bending, because it is directed along the radius of the block.

What happens next depends on the angle of incidence of the ray at the midpoint. Figure 13.23 shows the possibilities.

In Figure 13.23a, the angle of incidence is small, so most of the light emerges from the block. There is a faint reflected ray inside the glass block. The refracted ray bends away from the normal.

In Figure 13.23b, the angle of incidence has increased, so more light is reflected inside the block. The refracted ray bends even further away from the normal.

In Figure 13.23c, the refracted ray emerges along and parallel to the surface of the block for a particular angle of incidence. This angle is called the **critical angle**. Most of the light is reflected inside the block.

In Figure 13.23d, the angle of incidence is even greater and all of the light is reflected inside the block. No refracted ray emerges from the block.

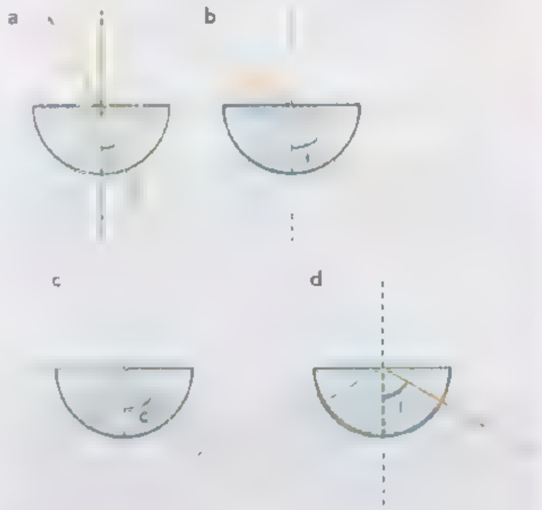


Figure 13.23: How a ray of light is reflected or refracted inside a glass block depends on the angle of incidence.

We have been looking at how light is reflected inside a glass block. We have seen that, if the angle of incidence is greater than the critical angle, the light is entirely reflected inside the glass. This is known as **total internal reflection (TIR)**:

- total, because 100% of the light is reflected
- internal, because it happens inside the glass
- reflection, because the ray is entirely reflected.

For total internal reflection to happen, the angle of incidence of the ray must be greater than the critical angle. The critical angle depends on the material being used. For glass, it is about 42°, depending on the type of glass. For water, the critical angle is greater, about 49°. For diamond, the critical angle is small, about 25°. Rays of light that enter a diamond are very likely to be totally internally reflected, so they bounce around inside, eventually emerging from one of the diamond's cut faces. That explains why diamonds are such sparkly jewels.

KEY WORDS

internal reflection: when a ray of light strikes the inner surface of a material and some of it reflects back inside it

critical angle: the minimum angle of incidence at which total internal reflection occurs

total internal reflection (TIR): when a ray of light strikes the inner surface of a material and 100% of the light reflects back inside it

EXPERIMENTAL SKILLS 13.2

Total internal reflection and the critical angle

You will shine a ray of light into a block and investigate when and how it is reflected.

You will need

- ray box with a slit
- power pack
- glass or Perspex® semi-circular block
- plain paper
- ruler and protractor

Safety: As you will be working in a darkened area you should keep your work area tidy to avoid trip hazards

CONTINUED

Getting started

How will you record the path of the rays of light that you observe as they pass through the block?

Method

1 Place the semi circular block on the paper and draw around it. Mark the exact centre of the straight side with a normal line.

2 Shine a ray of light into the block along the curved side so that it hits the midpoint of the straight side. Notice that the ray enters the block at right angles.

Figure 13.24: Shining the ray of light onto the glass block

3 Observe the path of the ray. You should see two rays. One is refracted as it emerges from the block and the other is reflected back into the block.

4 Move the ray box to increase the angle of incidence until the refracted ray emerges along the side of the block. The angle of incidence at which this happens is called the critical angle (c).

5 Mark the rays with crosses. Remove the block and draw the ray as it passes through the block.

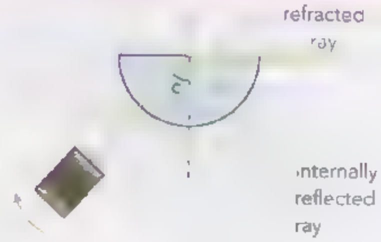


Figure 13.25: Critical angle.

6 Measure the critical angle, *c*.

7 Draw round the block again, and shine a ray into the block at an angle greater than the critical angle. The ray will be totally internally reflected.

Figure 13.26: Total internal reflection.

8 Mark the rays, remove the block and measure angles *i* and *r*.

Questions

1 Why is the ray not bent when it enters the block?

2 What was the critical angle for your block?

3 What conclusion can you draw from your measurements of angles *i* and *r* for the totally internally reflected ray?

Questions

17 Explain the meaning of the words 'total' and 'internal' in the expression 'total internal reflection'.

18 The critical angle for water is 49°. If a ray of light strikes the upper surface of a pond at an angle of incidence of 45°, will it be totally internally reflected? Explain your answer.

19 Look at Figure 13.27.

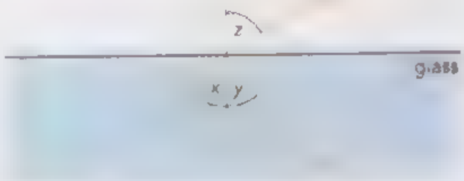


Figure 13.27

a Name angles x, y and z.

b Write down any relationships you know between the angles.

c Describe what will happen when angle x is increased.

Critical angle and refractive index

As we have seen, the critical angle depends on the material through which a ray is travelling. The greater the refractive index of the material, the smaller the critical angle (see the example of diamond in Worked Example 13.3). We can use the equation $n = \frac{\sin i}{\sin r}$ to see how critical angle c and refractive index n are related. To do this we need to be aware than the refractive index for glass relates to light passing from air to glass, not from glass to air. During your reflection and refraction experiments you always marked the rays with arrows. This is because all light rays are reversible. When you shine light from the opposite direction, you will get the same lines, only the arrows tell you which way the ray was travelling.

Figure 13.28 shows what happens when we reverse the rays.

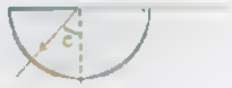


Figure 13.28: Reversing the rays

You can see from Figure 13.28 that the angle of incidence is 90°, and the angle of refraction as the ray goes into glass is the critical angle. Substituting in the equation gives:

$$n = \frac{\sin i}{\sin r} = \frac{\sin 90°}{\sin c}$$

Since $\sin 90° = 1$

$$n = \frac{1}{\sin c}$$

KEY EQUATION

critical angle

$$n = \frac{1}{\sin c}$$

Note that you need to know this equation, but you do not need to remember how it is derived.

Note also that the letter **c** is used both for critical angle **and** the speed of light. Read questions carefully and make sure you know which meaning is being used.

WORKED EXAMPLE 13.3

Find the critical angle, c, for diamond. Assume that refractive index $n = 2.40$

Step 1: Substitute the value of n in the equation.

$$\sin c = \frac{1}{n} = \frac{1}{2.40} = 0.417$$

Step 2: Rearrange to make c the subject:

$$c = \sin^{-1} 0.417$$

Step 3: Use a calculator (remember to check your calculator is set to degrees not radians) to find $\sin^{-1} 0.417$

Answer

$c = 24.6°$

Optical fibres

A revolution in telecommunications has been made possible by the invention of fibre optics. Telephone messages and other electronic signals such as internet computer messages or cable television signals are passed along fine glass fibres in the form of flashing laser light which is a digital signal. Figure 13.29a shows how fine these fibres can be. Each of these fibres is capable of carrying thousands of telephone calls simultaneously.

Figure 13.29: The use of fibre optics has greatly increased the capacity and speed of the world's telecommunications networks. Without this technology, cable television and the Internet would not be possible. a: Each of these very fine fibres of high-purity glass can carry many telephone messages simultaneously. b: Light travels along a fibre by total internal reflection.

Inside a fibre, light travels along by total internal reflection (see Figure 13.29b). It bounces along inside the fibre because, each time it strikes the inside of the fibre, its angle of incidence is greater than the critical angle. This means no light is lost as it is reflected. The fibre can follow a curved path and the light bounces along inside it, following the curve. For signals to travel over long distances, the glass used must be of a very high purity, so that it does not absorb the light.

Optical fibres are also used in medicine. An endoscope is a device that can be used by doctors to see inside a patient's body, for example, to see inside the stomach (Figure 13.30). One bundle of fibres carries light down into the body, while another bundle carries an image back up to the user. The endoscope may also have a small probe or cutting tool built in, so that minor operations can be performed without the need for major surgery.

Figure 13.30: Passing a fibre optic cable down the oesophagus to the stomach allows the doctor to see inside the patient without the need for major surgery.

Light can be used in sensory play to sooth or stimulate children with sensory processing issues. Using optical fibres means children can play freely with lights with no risk of electrocution or burning.

Questions

20 List three uses of total internal reflection.

21 a The critical angle for a material is 38°. Calculate its refractive index.

b Calculate the critical angle for diamond. Use data from Table 13.1.

22 Sketch a diagram to show how a ray of light can travel along a curved glass fibre. Indicate the points where total internal reflection occurs.

23 Figure 13.31 shows a bicycle reflector. It reflects light by total internal reflection.

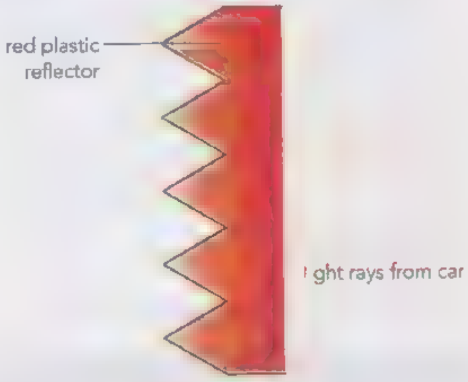


Figure 13.31: How light is reflected in a bicycle reflector.

a Why is light not refracted when it enters the plastic?

b What is the angle of incidence at the diagonal surface?

c Copy and complete the diagram in Figure 13.31 to show the path of the rays from the car.

d What can you deduce about the critical angle of the plastic?

13.4 Lenses

Lenses are all around us, for example in spectacles and cameras. Lenses are particularly important to scientists in instruments including microscopes and telescopes. Figure 13.32 shows two uses of lenses which helped to revolutionise science.

Converging and diverging lenses

Lenses can be divided into two types, according to their effect on light (Figure 13.33):

- **converging lenses** are fatter in the middle than at the edges
- **diverging lenses** are thinner in the middle than at the edges.

converging lens: a lens that causes rays of light parallel to the axis to converge at the principal focus

diverging lens: a lens that causes rays of light parallel to the axis to diverge from the principal focus

Figure 13.32a: More than 400 years ago, Galileo ground his own glass lenses to make telescopes like this. What he saw through them suggested the Earth was not the centre of the universe. **b:** A few years later, Van Leeuwenhoek used a simple single lens microscope to observe bacteria from his teeth, providing a clue as to how infectious diseases are spread.

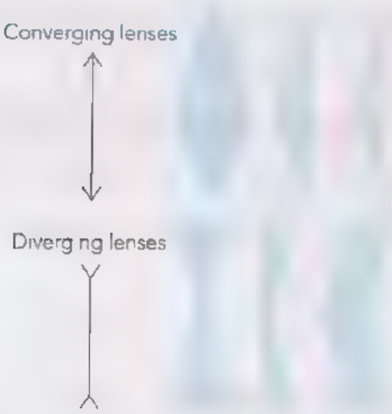


Figure 13.33: Converging lenses are fattest in the middle. Diverging lenses are thinnest in the middle. They are given these names because of their effect on parallel rays of light. Usually, we simply draw the cross section of the lens.

You have probably used a magnifying glass to look at small objects. This is a converging lens. 'Converging' means bringing together. You may even have used a magnifying glass to focus the rays of the Sun onto a piece of paper, to set fire to it. (More than a thousand years ago, an Arab scientist described how people used lenses for starting fires.)

Figure 13.34a shows how a converging lens focuses the parallel rays of the Sun. On one side of the lens, the rays are parallel to the **principal axis** of the lens. After they pass through the lens, they converge on a single point: the **principal focus** (or **focal point**). After they have passed through the principal focus, they spread out again. A converging lens can be used to produce a beam of parallel rays. A source of light, such as a small light bulb, is placed at the principal focus. As they pass through the lens, the rays are bent so that they become a parallel beam (Figure 13.34b). This diagram is the same as Figure 13.34a, but in reverse.

A converging lens is so-called because it makes parallel rays of light converge. The principal focus is the point where the rays are concentrated together, and where a piece of paper needs to be placed if it is to be burned. The distance from the centre of the lens to the principal focus is called the **focal length** of the lens. The fatter the lens, the closer the principal focus is to the lens. A fat lens has a shorter focal length than a thin lens. Figure 13.35 shows this.

KEY WORDS

principal axis: the line passing through the centre of a lens perpendicular to its surface

principal focus/focal point: the point at which rays of light parallel to the principal axis converge after passing through a converging lens

focal length: the distance from the centre of the lens to its principal focus

Figure 13.35a: A fatter lens is more powerful so bends the light more. This gives a shorter focal length. **b:** A thinner lens is not as powerful and does not bend the light as much.

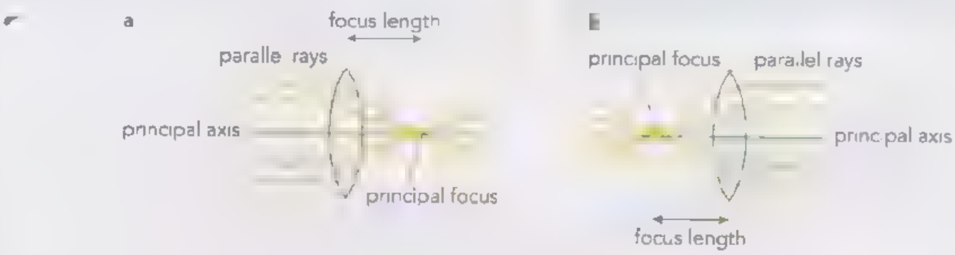


Figure 13.34: The effect of a converging lens on rays of light. **a:** A converging lens makes parallel rays converge at the principal focus. **b:** Rays from the principal focus of a converging lens are turned into a parallel beam of light.

Lenses work by refracting light. When a ray strikes the surface of the lens, it is refracted towards the normal. When it leaves the glass of the lens, it bends away from the normal. The clever thing about the shape of a converging lens is that it bends all rays just enough for them to meet at the principal focus.

Forming a real image

When the Sun's rays are focused onto a piece of paper, a tiny image of the Sun is created. It is easier to see how a converging lens makes an image if you focus an image of a light bulb or a distant window onto a piece of white paper. The paper acts as a screen to catch the image. (Be careful if you try this yourself – you could set fire to the paper or burn yourself. And remember: never look directly at the Sun.)

Figure 13.36 shows an experiment in which an image of a light bulb (the object) is formed by a converging lens. The image in the raindrop in Figure 13.1 was formed in the same way

Figure 13.36: Forming a real image of a light bulb using a converging lens. The image is upside down on the screen at the back right.

Images can be described in terms of their size (enlarged, the same size, or diminished), which way up they are (inverted or upright), and where they are formed

[illegible]

enlarged: used to describe an image which is bigger than the object

diminished: used to describe an image which is smaller than the object

inverted: used to describe an image which is upside down compared to the object

upright: used to describe an image which is the same way up as the object

The image of the lightbulb in Figure 13.36 is

- inverted
- diminished
- nearer to the lens than the object
- real.

We say that the image is real, because light really does fall on the screen to make the image. If light only appeared to be coming from the image, we would say that the image was virtual. The size of the image depends on how fat or thin the lens is.

Drawing ray diagrams for lenses

We can explain how this real image is formed using a ray diagram. These ray diagrams are drawn to scale and show the path of two particular rays. The steps needed to draw an accurate ray diagram are shown in Worked Example 13.4. Remember that it helps to work on squared paper or graph paper when drawing a ray diagram

Draw a ray diagram to find the image formed of a 3 cm tall object placed 12 cm from a converging lens which has a focal length of 5 cm.

Step 1: Draw the lens (a simple outline shape will do) with a horizontal axis through the middle of it.

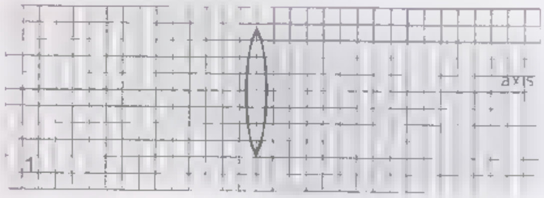


Figure 13.37a

Step 2: Mark the positions of the principal focus (F) on either side, at 5 cm from the centre of the lens. Mark the position of the object, O, along with a 3 cm arrow standing on the axis, . Place the arrow 12 cm from the lens.

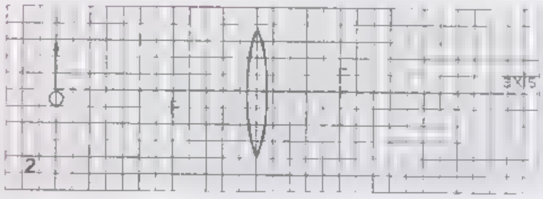


Figure 13.37b

Step 3: Draw ray 1, a straight line from the top of the object arrow which passes undeflected through the middle of the lens.

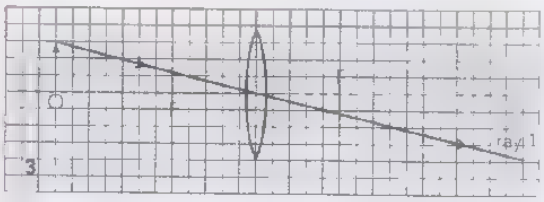


Figure 13.37c

Step 4: Draw ray 2 from the top of the object arrow parallel to the principal axis. As it passes through the lens, it is refracted through the principal focus. To make things easier when we draw ray diagrams, we only show rays bending once, at the centre of the lens.

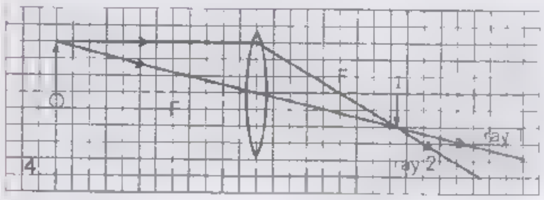


Figure 13.37d

Look for the point where the two rays cross. This is the position of the top of the image (I).

With an accurately drawn ray diagram, you can see that the image is inverted, diminished and real.

So, to construct a ray diagram like this, draw two rays starting from the top of the object:

- ray 1: unrefracted through the centre of the lens
- ray 2: parallel to the axis and then refracted through the principal focus.

ACTIVITY 13.3

Ray diagrams

Imagine you work for a company which makes cameras and projectors. You have been asked to produce short, technical guides explaining the use of lenses in these products.

Drawing ray diagrams lets us predict what an image will look like. A lens can make different images depending on its position. Draw the following ray diagrams:

- A lens with a focal length of 3 cm with the object 8 cm from the lens.
- The same lens but with the object 5 cm from the lens.

Describe the image formed in each case. Which is for a camera, and which for a film projector?

Draw diagrams to investigate the difference the thickness of a lens makes to the image. Remember, a fat lens has a short focal length, a thin lens has a longer focal length.

[illegible]

Swap ray diagrams with a partner and check if they are correctly drawn.

Give them a smiley face, straight face or sad face for each of the following features:

- axis drawn horizontally through the middle of the lens
- focal point, F, marked on each side of the lens
- ray from the top of the object passing though the centre of the lens without being deflected
- ray from the top of the object parallel to the axis striking the lens then passing through the principal focus
- rays drawn as straight lines using a ruler
- correct arrows on both rays
- image clearly marked, including which way up it is.

Discuss what, if anything, was missing and how you can both improve your diagrams.

Questions

24 Copy and complete these sentences:

A converging lens refracts parallel rays of light to a point called the ______.

The distance from this point to the lens is called the ______.

The fatter the lens the ______ this distance will be.

25 Copy and complete the ray diagrams in Figure 13.38 to show what happens when the rays hit the lenses.

Figure 13.38: Ray diagrams.

Magnifying glasses

A magnifying glass is a converging lens. You hold it close to a small object and peer through it to see a magnified image. Figure 13.39 shows how a magnifying glass can help to magnify print for someone with poor eyesight.

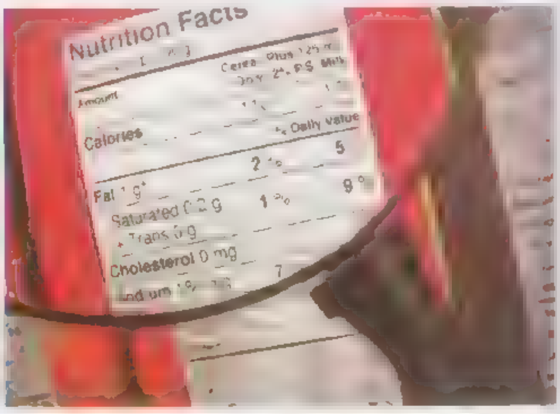


Figure 13.39: A converging lens produces a magnified image making small print easier to read.

[illegible] lens than the principal focus. We can draw a ray diagram using the same two rays as in Figure 13.40.

- Ray 1 is unrefracted as it passes through the centre of the lens.

- Ray 2 starts off parallel to the axis and is refracted by the lens so that it passes through the principal focus.

Rays 1 and 2 do not cross over each other. They are diverging (spreading apart) after they have passed through the lens. However, by extending the rays backwards, as shown by the dashed lines, we can see that they both appear to be coming from a point behind the object. This is the position of the image (I). We draw dashed lines because light does not actually travel along these parts of the rays. We cannot catch the image on a screen, because there is no light there.

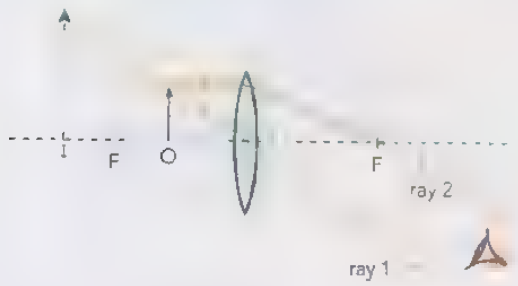


Figure 13.40: A ray diagram to show how a magnifying glass works. The object is between the lens and the focus. The image produced is virtual. To find its position, the rays have to be extrapolated back (dashed lines) to the point where they cross.

From the ray diagram (Figure 13.40), we can see that the image produced by a magnifying glass is:

- upright
- enlarged
- further from the lens than the object
- virtual

So, if you read a page of a book using a magnifying glass, the image you are looking at is behind the page that you are reading. This image is a virtual image.

Using lenses to correct eyesight problems

Our eyes contain converging lenses which form an image on the retina at the back of the eye. The lenses in our eyes are flexible and muscles can change the shape and strength of the lens. This allows us to focus on objects at different distances. Figure 13.41a shows an eye forming an image of a distant object. Figure 13.41b shows the eye focusing on a much closer object. The light from the closer object is diverging so the lens needs to be thicker and stronger to form an image on the retina.

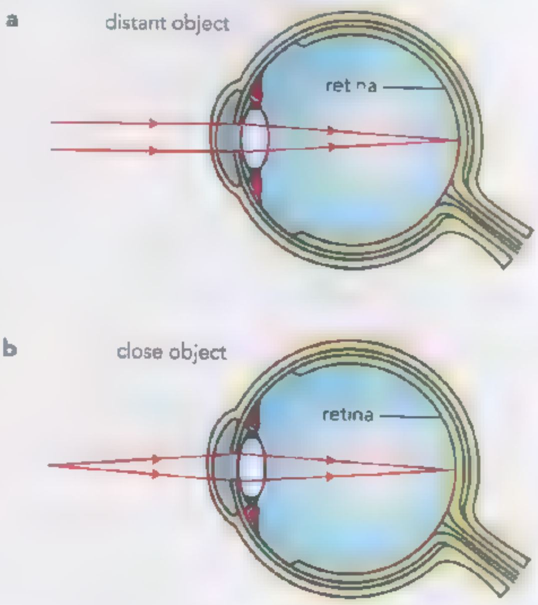


Figure 13.41a: Parallel light from a distant object is focused by a weak lens. **b:** Diverging light from a close object needs a stronger lens.

Some eyes are unable to change their strength enough to focus on either close or distant objects. An extra lens, worn as spectacles or contact lenses, can work with the eye lens to let it focus as needed.

Short sight

A person with short sight can see close up objects clearly, but cannot form a clear image of distant objects. The image is formed in front of the retina. This is usually because the eyeball is slightly too long so that the rays meet in front of the retina. To correct this, a diverging lens is used to make the rays from the distant object diverge. The eye lens is then able to form a focused image. Figure 13.42 shows the problem and how it is corrected.

Figure 13.42a: With short sight, the image is formed before the retina b: Using a diverging lens to help the lens in the eye to form an image on the retina.

Figure 13.43: Without glasses, distant objects appear blurred to a short sighted person. The diverging lens in the glasses lets the person focus on distant objects.

Long sight

A long-sighted person has the opposite problem. A long sighted eye can focus on distant objects but not close objects. This can be because the eyeball is too short, or the lens cannot become strong enough so the rays from a close object cannot be converged enough to a form an image on the retina. A converging lens causes the rays to converge, allowing the eye lens to form a focused image of close objects, as shown in Figure 13.44.

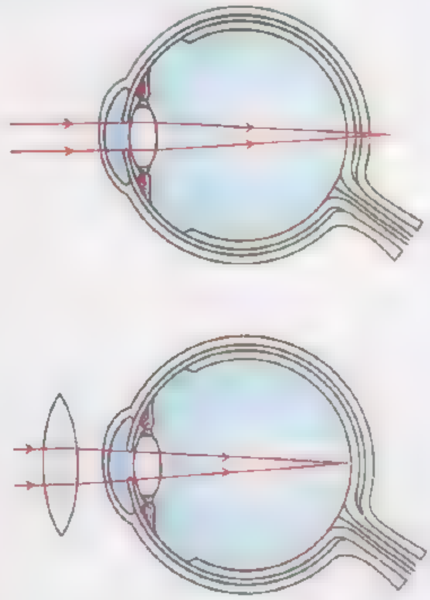


Figure 13.44a: With long sight, the image is formed behind the retina b: A converging lens works with the lens in the eye to form an image on the retina

Questions

26 Look at Figure 13.40. How can you tell from the diagram that the image formed by the magnifying glass is a virtual image?

27 a A converging lens has focal length 3 cm. An object, 2 cm tall, is placed 5 cm from the centre of the lens, on the principal axis. Draw an accurate ray diagram to represent this.

b Use your diagram to determine the distance of the virtual image formed from the lens, and the height of the image.

28 Figure 13.45 shows an eye looking at a distant object. The person sees a blurred image.

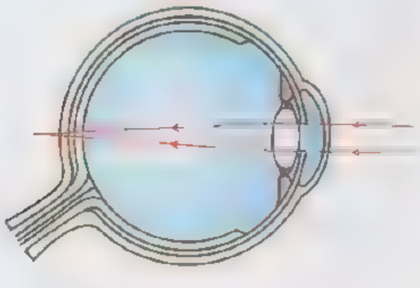


Figure 13.45: Eye looking at a distant object

a Name the eyesight problem this person has.

b Describe how the shape of the eye causes this problem.

c Draw a diagram to show how a lens can be used to help this person to see a focused image of the distant object.

13.5 Dispersion of light

When white light passes through glass, it refracts as it enters and leaves the glass, and can be split into a **spectrum** of colours. Figure 13.46a shows light being refracted as it passes through a glass prism. You can see that the colours merge into one another, and they are not all of equal widths in the spectrum. A rainbow is a naturally occurring spectrum. White light from the Sun is split up into a spectrum of colours as it enters and leaves droplets of water in the air. It is also reflected back to the viewer by total internal reflection, which is why you must have the Sun behind you to observe a rainbow.

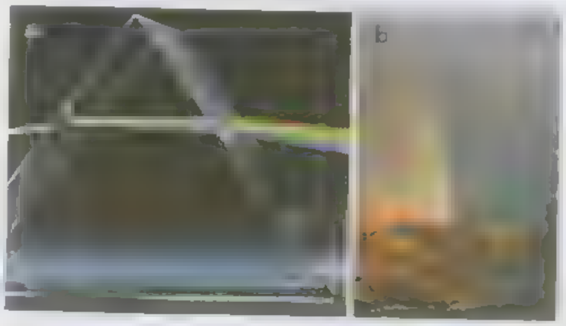


Figure 13.46a: White light is dispersed by a prism
b: Raindrops take the place of the prism to form a rainbow.

This splitting up of white light into a spectrum is known as **dispersion**. Isaac Newton set out to explain how it happens. It had been suggested that light is coloured by passing it through a prism. Newton showed that this was the wrong idea by arranging for the spectrum to be passed back through another prism. The colours recombined to form white light again. He concluded that white light is a mixture of all the different colours of the spectrum. Newton described the visible light spectrum as being made up of seven colours – red, orange, yellow, green, blue, indigo and violet. You may wonder why indigo and violet are separate rather than just being purple. This is because, in the 17th century, seven was considered to be a mystical number. So, Newton wanted seven colours not just six. The colours can be remembered as a name, Roy G Biv.

Figure 13.47: The first prism refracts the light causing it to disperse. The second prism refracts the light back, causing the colours to recombine.

So, what happens in a prism to produce a spectrum? As the white light enters the prism, it slows down. We say that it is refracted and, as we have seen, its direction changes. Dispersion occurs because each colour is refracted by a different amount (Figure 13.47). Violet light slows down the most, and so it is refracted the most. Red light is least affected.

spectrum (plural: spectra) waves, or colours, of light, separated out in order according to their wavelengths

dispersion: the separation of different wavelengths of light because they are refracted through different angles

Light of a single colour is not dispersed by a prism. It is refracted so that it changes direction, but it is not split up into a spectrum. You can see this in Figure 13.48. This is because it is light of a single colour. This light is described as **monochromatic** (mono = one, chromatic = coloured). Monochromatic light is light of a single frequency.

Figure 13.48: Monochromatic light from a laser is not dispersed by a prism as the light is all one frequency.

KEY WORD

monochromatic: describes a ray of light (or other electromagnetic radiation) of a single wavelength

Questions

29 Copy and complete these sentences.

When light enters glass it slows down, causing it to change direction. This is called ______

Red light changes direction ______ than violet light

The light is split into different colours. This is called ______

30 Draw a diagram to show how white light can be dispersed into a spectrum using a glass prism. Label the red and violet light.

31 List the colours of the visible spectrum in order starting with the colour which is refracted the least

When we study light, we use very similar words and diagrams for reflection and refraction. Have you found this difficult? How have you learnt the rules for ray diagrams? How successful have you been?

Light fantastic

In this chapter you have seen lots of optical effects caused by the reflection and refraction of light. Some are useful, some are a nuisance. Your task is to investigate, illustrate and explain one of these effects.

Your results should be presented as a poster and should include

- a photo – preferably one you have taken – of the effect
- a ray diagram to show what is happening
- a description of the scientific laws and principles which explain the effect.

You can use an effect you have seen in class, such as the formation of an image in a plane mirror, or you can apply what you have learnt to a new situation. For example:

- How does the turtle in Figure 13.49 see itself? (With a waterproof camera you could take a similar photo of yourself in a swimming pool.)
- Why do diamonds sparkle so much?
- Why do lenses create upside down images?
- How can interior designers use mirrors to make a space seem bigger?
- How does the eye form an image (and how can glasses help solve vision problems)?
- How does a periscope work?

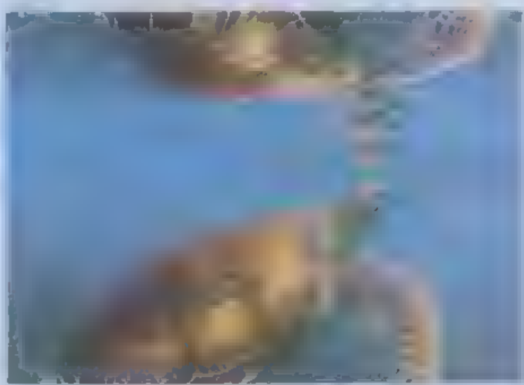
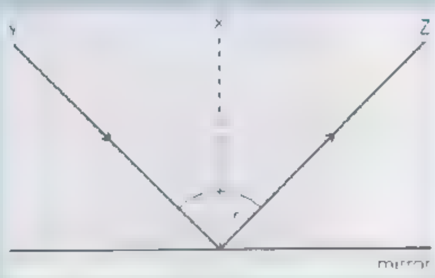


Figure 13.49: Reflection at the surface of the water allows this turtle to see itself

The law of reflection: angle of incidence = angle of reflection.
The image in a plane mirror is upright, as far behind the mirror as the object is in front and swapped round left to right
The image in a plane mirror is virtual
Refraction is the bending of light as it goes from one substance to another.
Refraction is caused by light travelling at different speeds in different materials.
When light passes from air to glass it bends towards the normal When it passes from glass to air it bends away from the normal.
When light travelling through glass hits a boundary with air, some light passes from glass to air, some light is internally reflected back into the glass.
When the angle of incidence in glass is equal to, or greater than, the critical angle, all the light is reflected back into the glass. This is total internal reflection.
The refractive index is a measure of how much light is slowed, or bent, by a material
Refractive index can be calculated using the equation $n = \frac{\sin i}{\sin r}$
Refractive index $= \frac{1}{\text{critical angle}}$.
Optical fibres can transmit information rapidly and efficiently using total internal reflection This is useful in telecommunications and medicine.
Converging lenses bend parallel rays together so they meet at a point called the principal focus.
Drawing a ray parallel to the axis, and a ray which strikes the centre of a lens allows us to draw a ray diagram and find the type of image formed.
A magnifying glass produces a virtual image
Our eyes use a flexible convex lens to form images.
A short-sighted eye has a lens which is too powerful This can be corrected using a diverging lens.
A long-sighted eye has a lens which is too weak This can be corrected using a converging lens.
White light can be dispersed by passing it through a glass prism. This creates the visible spectrum.

[illegible]

1 The diagram shows a ray of light striking a plane mirror



Which row gives the correct labels for the diagram? [1]

	X	Y	Z
A	normal	incident ray	angle of refraction
B	angle of incidence	incident ray	normal
C	reflected ray	normal	angle of reflection
D	normal	incident ray	reflected ray

2 Which one of the following statements about the image formed in a plane mirror is true? [1]

A The image can be formed on a screen

B The image is diminished

C The image is upright.

D The image is on the surface of the mirror

3 A ray of light passes from air to glass at an angle of 30° Which statement correctly describes what happens? [1]

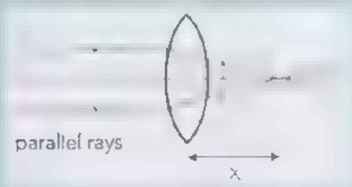
A The ray bends towards the normal

B The ray passes through the glass without bending.

C The ray is totally internally reflected.

D The ray bends away from the normal

4 This diagram shows light being refracted by a converging lens.



a What name is given to the distance marked X? [1]

b This diagram shows one ray of light passing through the lens. The lens can be used to form an image of an object.

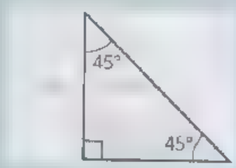
Copy the diagram and draw another ray to complete it. Draw an arrow to represent the image. **[3]**

c Choose **two** of these words to describe the image in b. **[2]**

upright   inverted   diminished   enlarged

[Total: 6]

5 This diagram shows a ray of light entering a glass prism. The refractive index of the glass is 42°.



a [illegible] why the ray is not refracted as it enters the glass. **[1]**

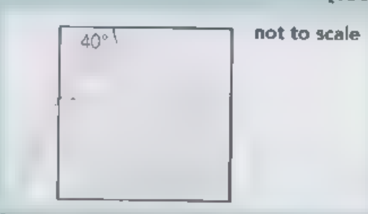
b Copy and complete the diagram to show what happens to the ray **[1]**

c What name is given to the effect you have drawn? **[1]**

d If the prism was removed, what other piece of apparatus could produce the same effect on the light ray? **[1]**

[Total: 6]

6 The diagram shows a ray of light striking the inner surface of a glass block. The critical angle for the glass is 42°.



a Copy the diagram. Without calculating, continue the ray from the point where it strikes the surface until it leaves the block **[2]**

b What can you say about the speed of light in the glass block? **[1]**

c [illegible] the refractive index of the glass.
Write down the equation you use **[2]**

d Calculate the angle of incidence at which the ray enters the glass block **[2]**

[Total: 7]

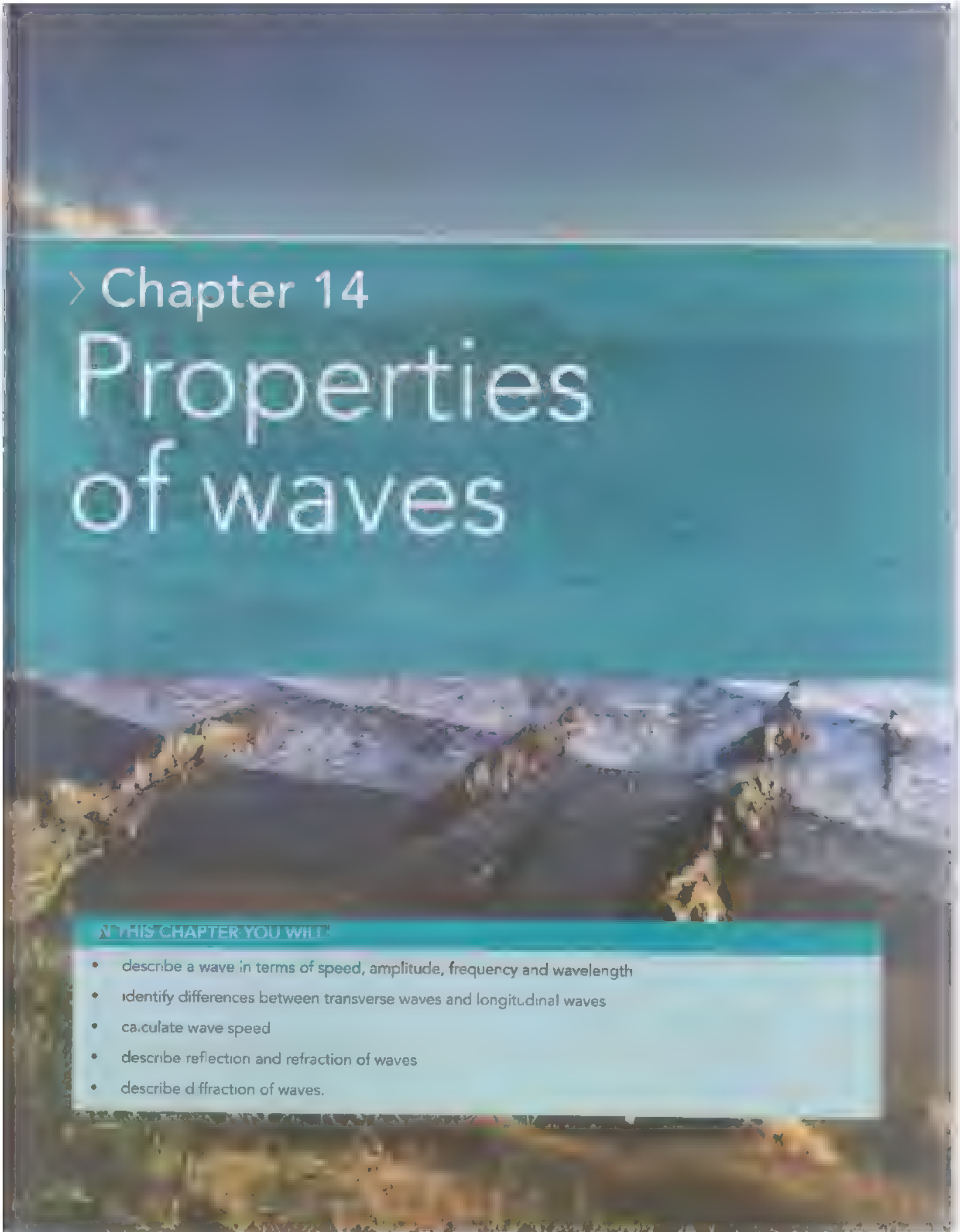
set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

calculate: work out from given facts, figures or information

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively

[illegible]	See Topic…	Needs more work	Almost there	Confident…
Describe how an image is formed in a plane mirror	13.1			
Recall and use the equation: angle of incidence = angle of reflection.	13.1			
Draw a ray diagram to show the formation of a virtual image in a plane mirror.	13.1			
Describe an experiment to investigate how light is refracted when it passes through a glass block.	13.2			
Draw a labelled diagram of light passing through a glass block, labelling the normal and the angles of incidence and refraction.	13.2			
Describe internal reflection and recall that if the angle of incidence is greater than the critical angle, total internal reflection occurs.	13.3			
Recall and use the equations: $n = \frac{\sin i}{\sin r}$ $n = \frac{1}{\sin \text{critical angle}}$	13.2, 13.3			
Describe and explain how total internal reflection is used in telecommunications and medicine.	13.3			
Draw a fully labelled ray diagram to show the formation of a real image by a converging lens.	13.4			
Describe the nature of the image formed	13.4			
Draw a fully labelled ray diagram to show the formation of a virtual image by a converging lens and explain how this is used in a magnifying glass.	13.4			
Draw diagrams to show the correction of long and short-sightedness using lenses.	13.4			
Name the seven colours of the visible spectrum in the correct order.	13.5			



Chapter 14

Properties of waves

IN THIS CHAPTER YOU WILL:

- describe a wave in terms of speed, amplitude, frequency and wavelength
- identify differences between transverse waves and longitudinal waves
- calculate wave speed
- describe reflection and refraction of waves
- describe diffraction of waves.

In a group, discuss all the different types of wave you can think of.

What do these waves have in common? What do waves do?

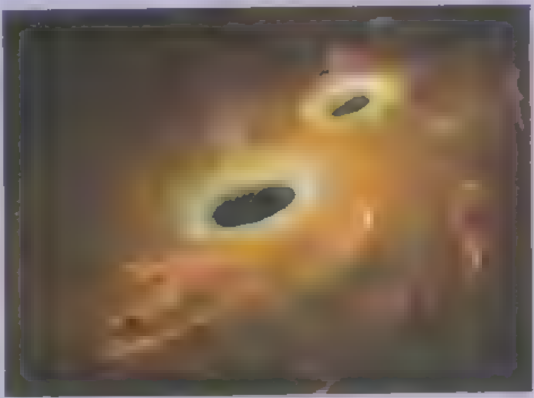


Figure 14.1: Einstein's last prediction was confirmed after 100 years

Einstein hypothesized that the universe is made of a fabric that he called the space-time continuum. He predicted that interactions between massive objects would create ripples in space-time in much the same way that throwing a stone into a pond causes ripples in the water.

The ripples are very hard to detect as they are tiny. The space-time continuum is very stiff and only really huge events cause any measurable ripples. Lasers are used to pick up tiny variations in space-time that could be caused by a passing gravitational wave. In 2016, scientists working at the Laser Interferometer Gravitational-Wave observatory (LIGO) detected a ripple in space-time caused by two black holes spiralling towards each other and merging into one.

The discovery of gravitational waves is important for two reasons.

- It provides further evidence to support Einstein's theory of relativity.
- Gravitational waves travel huge distances without the signal being affected. This could allow astronomers to investigate areas of the universe which we cannot access using light. This could provide information about the Big Bang, and the existence of dark matter.

The idea of a wave is a very useful model in physics. Physicists talk about light waves, sound waves, electromagnetic waves, and so on. It is easy to see how waves behave in water and springs. It is not obvious that light, gravity and sound are waves in the way we think of waves in the sea. In this chapter, we will investigate waves in water and springs, and see how these waves can act as a good model for both light and sound.

Discussion questions

1. Does the discovery of gravitational waves prove that Einstein was right?
2. A member of the LIGO team commented that the discovery of gravitational waves means we are at the start of the era of gravitational wave astronomy. Gravitational waves will provide us with information that will help us to understand the universe. Discuss other ways in which humans have used waves to gather information about the earth and beyond.

14.1 Describing waves

Physicists use waves as a **model** to explain the behaviour of light, sound and electromagnetic radiation. Water waves can help us understand the behaviour of waves as they are easy to observe. Waves are what we see on the sea or a lake, but physicists have a more specialised idea of waves. We can begin to understand this model in the laboratory using a **ripple tank** (Figure 14.2)

A **ripple tank** is a shallow glass-bottomed tank containing a small amount of water. A light shining downwards through the water casts a shadow of the ripples on the floor below, showing the pattern that they make

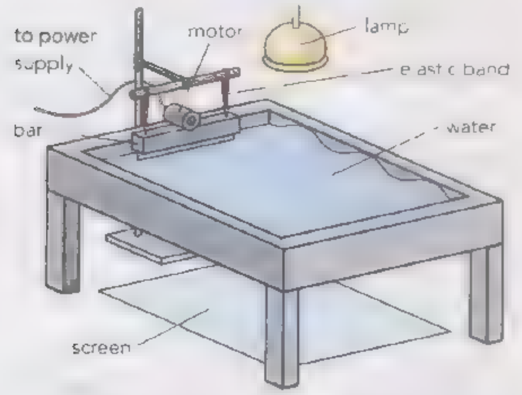


Figure 14.2: The ripples on the surface of the water in this ripple tank are produced by the bar, which vibrates up and down. The pattern of the ripples is seen by shining a light downwards through the water. This casts a shadow of the ripples on the screen beneath the tank.

Figure 14.3 shows two patterns of ripples, straight and circular, which are produced in different ways.

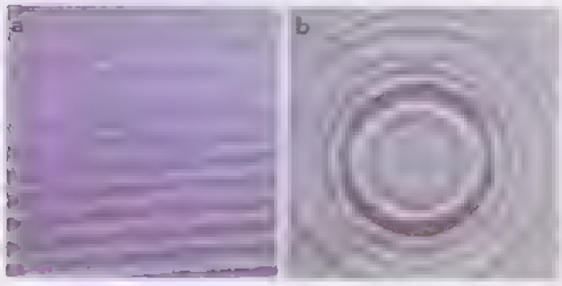


Figure 14.3: Two patterns of ripples on water. **a:** Straight ripples are a model for a broad beam of light. **b:** Circular ripples are a model for light spreading out from a lamp

One way of making ripples on the surface of the water in a ripple tank is to have a wooden bar that just touches the surface of the water (as in Figure 14.2). The bar vibrates up and down at a steady rate. This sends equally spaced straight ripples across the surface of the water.

A spherical dipper can produce a different pattern of ripples. The dipper just touches the surface of the water. As it vibrates up and down, equally spaced circular ripples spread out across the surface of the water.

In each case, the ripples are produced by something vibrating up and down vertically, but the ripples move out horizontally. The vibrating bar or dipper pushes water molecules up and down. Each molecule drags its neighbours up and down. These then start their neighbours moving, and so on. Each molecule simply moves up and down. Energy is transferred by the wave, but the water molecules remain in the same place after the wave has passed. A wave transfers energy but not matter.

How can these patterns of ripples be a model for the behaviour of light? The straight ripples are like a beam of light, perhaps coming from the Sun. The ripples move straight across the surface of the water, just as light from the Sun travels in straight lines. The circular ripples spreading out from a vibrating dipper are like light spreading out from a lamp. (The dipper is the lamp.) In this chapter we will use waves in the ripple tank as a model to help us understand the behavior of light and sound waves.

model: a way of representing a system in order to understand how it functions

ripple tank: a shallow water tank used to demonstrate how waves behave

ripple: a small uniform wave on the surface of water

Wavelength and amplitude

Waves are often represented by a wavy line, as shown in Figure 14.4. We have already used this idea for sound waves (in Chapter 12) and we will do so again for electromagnetic waves (in Chapter 15). This wavy line is like a downward slice though the ripples in the ripple tank. It shows the succession of crests (also called peaks) and troughs of which the ripples are made.

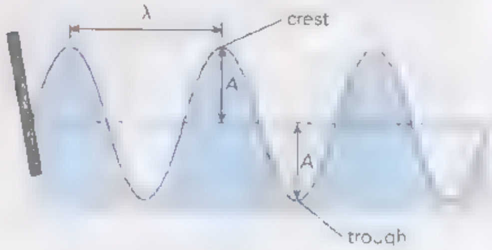


Figure 14.4a: A sideways view of a wave in a ripple tank.

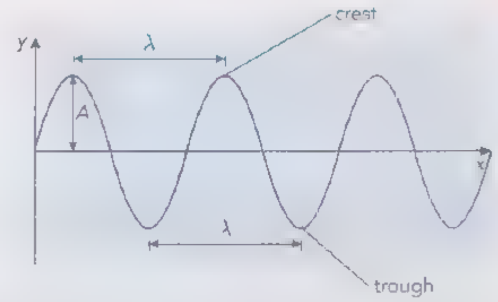


Figure 14.4b: The same wave as **a** represented as a smoothly varying wavy line on a graph. This shape is known as a sine wave. If you have a graphics calculator, you can use it to display a graph of $y = \sin x$, which will look like this graph

The graph in Figure 14.4b shows a wave travelling from left to right. The horizontal axis (x-axis) shows the distance, x, travelled horizontally by the wave. The vertical axis (y-axis) shows how far (distance y) the surface of the water has been displaced from its normal level. We can think of the x-axis as the level of the surface of the water when it is undisturbed. The blue line on the graph shows how far the surface of the water has been displaced from its undisturbed level.

Two measurements are marked on the graph. These define quantities used to describe waves.

- The **wavelength** λ of a wave is the distance from one crest of the wave to the next or between any two points on the wave which are in step. Since the wavelength is a distance, it is measured in metres, m. Its symbol is λ, the Greek letter lambda.
- The amplitude, A, of a wave is the maximum distance that the surface of the water is displaced from its undisturbed level, that is, the height of a crest (or the depth of a trough). For ripples on the surface of water, the amplitude is a distance, measured in metres, m. Its symbol is A.

For ripples in a ripple tank, the wavelength might be a few millimetres and the amplitude a millimetre or two. Waves on the open sea are much bigger, with wavelengths of tens of metres, and amplitudes varying from a few centimetres up to several metres.

crest/peak: the highest point of a wave

trough: the lowest point of a wave

wavelength: the distance between two adjacent crests (or troughs) of a wave

Frequency and period

As the bar in the ripple tank vibrates, it sends out ripples. Each up-and-down movement sends out a single ripple. The more times the bar vibrates each second, the more ripples it sends out. This is shown in the graph in Figure 14.5. Take care! This looks very similar to the previous wave graph in Figure 14.4, but here the horizontal axis shows time, t, not distance, x. This graph shows how the surface of the water at a particular point moves up and down as time passes.

From the representation of the wave in Figure 14.5, we can define two quantities for waves in general:

- The frequency, f, of a wave is the number of waves sent out each second. Frequency is measured in hertz, Hz. One hertz (1 Hz) is one complete wave or ripple per second.
- The period, T, of a wave is the time taken for one complete wave to pass a point. The period is measured in seconds, s.

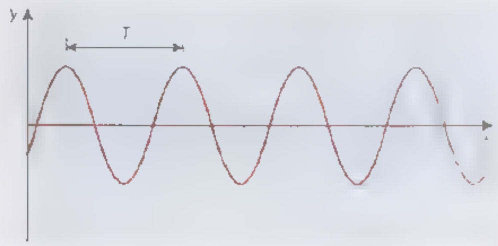


Figure 14.5: A graph to show the period of a wave. Notice that this graph has time, t, on its horizontal axis

We have already discussed the frequency and period of a sound wave in Chapter 12. It is always important to check whether a wave graph has time, t, or distance, x, on its horizontal axis.

The frequency of a wave is the number of waves made each second, or the number of waves passing a point per second. The period is the number of seconds it takes for each wave to pass a point. Frequency, f, and period, T, are obviously related to each other. Waves with a short period have a high frequency.

$$\text{frequency (Hz)} = \frac{1}{\text{period (s)}}$$

$$f = \frac{1}{T}$$

$$\text{period (s)} = \frac{1}{\text{frequency (Hz)}}$$

$$T = \frac{1}{f}$$

Waves on the sea might have a period of 10 seconds. Their frequency is therefore about 0.1 Hz. A sound wave might have a frequency of 1000 Hz. Its period is therefore $\frac{1}{1000\,\text{s}}$, which means that a wave arrives every 1 ms (one millisecond).

Wave speed

The **wave speed** is the rate at which the crest of a wave travels. For example, it could be the speed of the crest of a ripple travelling over the surface of the water. Speed is measured in metres per second (m/s).

Waves can have very different speeds. Ripples in a ripple tank travel a few centimetres per second. Sound waves travel at 330 m/s through air. Light waves travel at about 300 000 000 m/s through air.

KEY WORD

wave speed: the speed at which a wave travels

Waves and energy

We can also think of the speed of a wave as the speed at which it transfers energy from place to place.

Think of the Sun. It is a source of energy. Its energy reaches us in the form of radiation – light waves and infrared waves – which travels through the vacuum of space and which is absorbed by the Earth.

Think of a loudspeaker. It vibrates and causes the air nearby to vibrate. These vibrations spread out in the air as a sound wave. When they reach our ears, our eardrums vibrate. Energy has been transferred by the sound waves to our ears.

The bigger the amplitude, the more energy the wave transfers. A large amplitude means a bright light or a loud sound.

If you have ever been knocked over by a wave in the sea, you will know that water waves also carry energy. It is important to remember that, when a wave travels from one place to another, it is not matter that is moving. The wave is moving, and it is carrying energy. It may move through matter or even through a vacuum, but the matter itself is not transferred from place to place. A wave transfers energy without transferring matter.

Earthquakes show the huge amounts of energy which waves can transfer. Vibrations passing through the Earth can cause buildings to collapse. A seismometer records the vibrations caused by an earthquake.

Figure 14.6a: Vibrations caused by shifts in the Earth's tectonic plates can cause devastation. **b:** The seismometer records the amplitude and frequency of the vibrations.

Transverse and longitudinal waves

Ripples in a ripple tank are one way of looking at the behaviour of waves. You can model waves in other ways. As shown in Figure 14.7, a stretched slinky spring can be used to model waves. Fix one end of the spring and move the other end from side to side (Figure 14.7a). You will see that a wave travels along the spring. (You may also notice it reflecting from the fixed end of the spring.) You can demonstrate the same sort of wave using a stretched rope or piece of elastic. You can see the link between frequency and wavelength by changing the rate at which you move the end of the spring up and down. Increasing the frequency decreases the wavelength.

A second type of wave can also be modelled with a stretched slinky spring. Instead of moving the free end from side to side, move it backwards and forwards (Figure 14.7b). A series of compressions travels along the spring. These are regions in which the segments of the spring are compressed together. In between are rarefactions, regions in which the segments of the spring are further apart. This type of wave cannot be demonstrated on a stretched rope.

The direction of propagation of a wave is the direction in which it travels. You can observe this by watching the movement of crests and troughs, or compressions and rarefactions.

The demonstrations in Figure 14.7 show the two different types of wave:

- **Transverse waves**: the particles carrying the wave move from side to side, at right angles to the direction of propagation of the wave.
- **Longitudinal waves**: the particles carrying the wave move back and forth, along the direction of propagation of the wave.

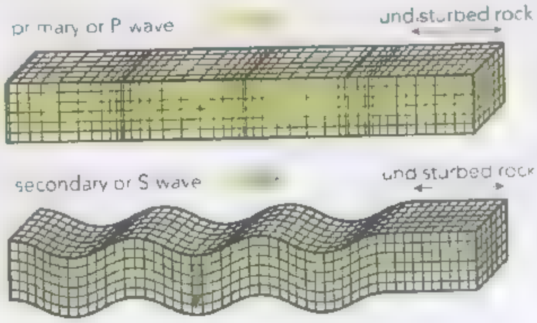


Figure 14.8: Primary and secondary seismic waves.

A ripple on the surface of water is an example of a transverse wave. The particles of the water move up and down as the wave travels horizontally.

In an earthquake there are two types of **seismic** waves: primary or **P-waves** and secondary or **S-waves**. P-waves are longitudinal. These waves are called primary waves as they travel faster than slower secondary waves and so are felt first. Secondary waves are transverse.

A sound wave is an example of a longitudinal wave. As a sound travels through air, the air molecules move back and forth as the wave travels. Table 14.1 lists examples of transverse and longitudinal waves.

Transverse waves	Longitudinal waves
ripples on water	sound
light and all other electromagnetic waves	primary seismic waves (P-waves)
secondary seismic waves (S-waves)	

Table 14.1: Transverse and longitudinal waves.

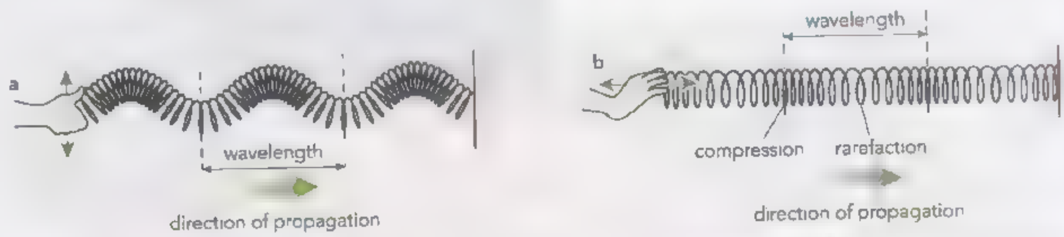


Figure 14.7: Modelling waves using a spring. **a:** A transverse wave on a stretched spring. It is made by moving the free end from side to side. **b:** A longitudinal wave on a stretched spring. It is made by pushing the free end back and forth, along the length of the spring.

transverse wave: a wave in which the vibration is at right angles to the direction of propagation of the wave

longitudinal wave: a wave in which the vibration is forward and back, parallel to the direction of propagation of the wave

seismic waves: waves caused by earthquakes

P-waves: fast moving, longitudinal seismic waves

S-waves: slow moving, transverse seismic waves

Questions

1 Copy and complete the following sentences.
   a A wave transfers ______ from place to place without transferring ______ .
   b In a ______ wave the vibrations are at right angles to the direction in which the wave travels. In a ______ wave the vibrations are back and forth along the direction of the wave.

2 The two waves in Figure 14.9 represent two light waves, X and Y.

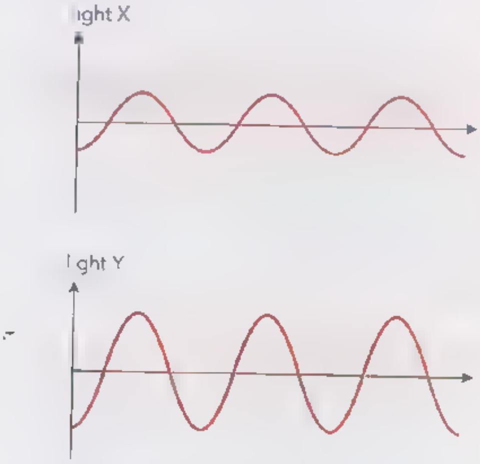


Figure 14.9: Two light waves.

Copy these sentences, selecting the correct answers from the brackets.
   a The two waves have {the same / different} wavelengths.
   b The two waves have {the same / different} amplitudes.
   c Light X will be {brighter / dimmer} than light Y.

3 Draw a wave and label the amplitude and the wavelength.

4 Give one example of a transverse wave and one example of a longitudinal wave.

5 Deduce the wavelength of the waves in Figure 14.10.

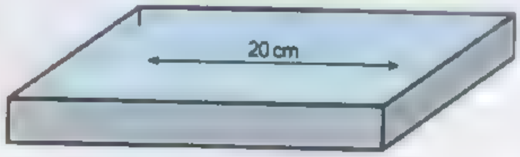


Figure 14.10: Waves

6 The bar of a ripple tank vibrates five times per second.
   a State the frequency of the waves it makes.
   b Find the period of the waves it makes.

7 A student sees a flash of lightning and, three seconds later, she hears the thunder.
   a Why does she see the lightning before she hears the thunder?
   b Light and sound are both types of waves. Copy and complete the following sentences, choosing the correct words from the brackets.
      i Light is a {transverse / longitudinal} wave. The vibrations are {parallel to / at right angles to} the direction of travel of the wave. These waves {can / cannot} travel through a vacuum.
      ii Sound is a {transverse / longitudinal} wave. The vibrations are {parallel to / at right angles to} the direction of travel of the wave. These waves {can / cannot} travel through a vacuum.
   c The speed of sound in air is 330 m/s. Calculate how far away the storm is from the student.

14.2 Speed, frequency and wavelength

How fast do waves travel across the surface of the sea? If you stand on the end of a pier, you may be able to answer this question.

Figure 14.11: By timing waves and measuring their wavelength, you can find the speed of waves

Suppose that the pier is 60 metres long, and that you notice that exactly five waves fit into this length (Figure 14.11). Using this information, you can deduce that the wavelength is:

$$\text{wavelength} = \frac{60\,\text{m}}{5}$$
$$= 12\,\text{m}$$

Now you time the waves arriving. The interval between crests as they pass the end of the pier is 4.0 seconds. How fast are the waves moving? One wavelength (12 metres) passes in 4.0 seconds. So the speed of the waves is:

$$\text{speed} = \frac{12\,\text{m}}{4.0\,\text{s}}$$
$$= 3.0\,\text{m/s}$$

The speed, v, frequency, f, and wavelength, λ, of a wave are connected. We can write the connection in the form of an equation:

speed (m/s) = frequency (Hz) × wavelength (m)

$$v = f\lambda$$

KEY EQUATION

wave speed = frequency × wavelength

$$v = f\lambda$$

Another way to think of this is to say that the speed is the number of waves passing per second multiplied by the length of each wave. If 100 waves pass each second (f = 100 Hz), and each is 4.0 m long (λ = 4.0 m), then 400 m of waves pass each second. The speed of the waves is 400 m/s.

WORKED EXAMPLE 14.1

An FM radio station broadcasts signals of wavelength 1.5 metres and frequency 200 MHz. What is their speed?

Step 1: Write down what you know, and what you want to know

f = 200 MHz = 200 000 000 Hz

$= 2 \times 10^8$ Hz

λ = 1.5 m

v = ?

Step 2: Write down the equation for wave speed. Substitute values and calculate the answer.

$v = f\lambda$

$v = 2 \times 10^8\,\text{Hz} \times 1.5\,\text{m}$

$= 3 \times 10^8$ m/s

Answer

The radio waves travel through the air at 3.0×10^8 m/s. (You might recognise this number as the speed of light.)

WORKED EXAMPLE 14.2

The highest note on a piano has a frequency of 4186 Hz. What is the wavelength of the sound waves produced when this note is played? Assume that the speed of sound in air = 330 m/s. Give your answer to two significant figures.

Step 1: Write down what you know, and what you want to know.

f = 4186 Hz

v = 330 m/s

λ = ?

Step 2: Write down the equation for wave speed. Rearrange it to make wavelength λ the subject.

$v = f\lambda$

$\lambda = \frac{v}{f}$

CONTINUED

Step 3: Substitute values and calculate the answer.

$$\lambda = \frac{330}{4186}$$

$$= 0.07166\ \text{m}$$

To 2 s.f. this is 0.072 m

Answer

The wavelength of the note in air is 0.072 metres.

Changing material, changing speed

When waves travel from one material into another, they usually change speed. Light travels more slowly in glass than in air. Sound travels faster in steel than in air. When this happens, the frequency of the waves remains unchanged. This means that their wavelength must change. This is illustrated in Figure 14.12, which shows light waves travelling quickly through air. They reach some glass and slow down, and their wavelength decreases. When they leave the glass, they speed up, and their wavelength increases again.

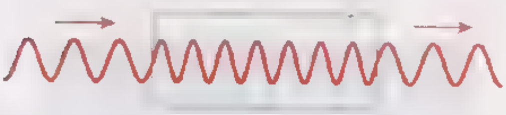


Figure 14.12: Waves change their wavelength when their speed changes. Their frequency remains constant. Here, light waves slow down when they enter glass and speed up when they return to the air

Questions

8 For the equation $v = f\lambda$, write down what each symbol represents and give their SI units.

9 Calculate the speed of water waves which have a wavelength of 3 m and a frequency of 0.5 Hz.

10 A wave in air has a frequency of 1100 Hz, an amplitude of 4 cm and a wavelength of 30 cm.
  a Calculate the speed of the wave.
  b Suggest what type of wave it is likely to be.
  c Calculate the period of the wave.

11 Blowing across pan pipes (Figure 14.13) creates a sound wave in the pipe.
Explain why the longer pipes produce lower pitched notes.

Figure 14.13: Pan pipes

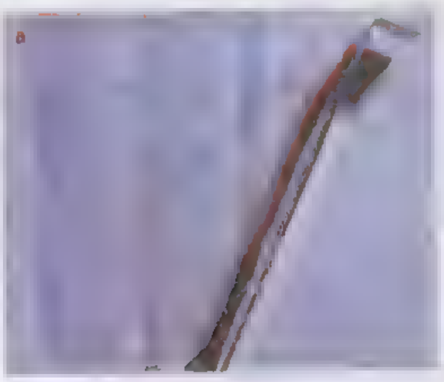
12 Which have the longer wavelength, radio waves of frequency 90 000 kHz or 100 MHz?

13 Sound waves get faster when they go from air into water. What happens to their:
  a speed?
  b wavelength?
  c frequency?
  d period?

14.3 Explaining wave phenomena

When we look at ripples on the surface of water in a ripple tank, we can begin to see why physicists say that light behaves as a wave. The ripples are much more regular and uniform than waves on the sea, so this is a good model system to look at.

Reflection of ripples



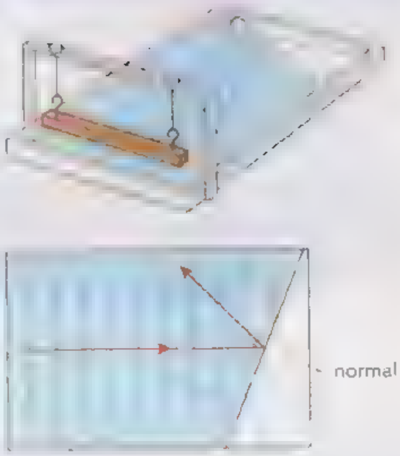


Figure 14.14: The reflection of plane waves by a flat metal barrier in a ripple tank. **a:** This criss-cross pattern is observed as the reflected ripples pass through the incoming ripples. **b:** How the ripples are produced. **c:** The arrows show how the direction of the ripples changes when they are reflected. The angle of incidence is equal to the angle of reflection, just as in the law of reflection of light.

Figure 14.14 shows what happens when a flat barrier is placed in the ripple tank. Figure 14.14a shows the pattern of the ripples observed, and Figure 14.14b shows how the ripples are produced. Straight ripples (plane waves) are reflected when they strike the flat surface of the barrier. The barrier acts like a mirror, and the ripples bounce off it. This shows an important feature of how waves behave. They pass through each other when they overlap.

Figure 14.14c shows a drawing of the same pattern. This is an overhead view of the ripples. The blue lines represent the tops of the ripples. These lines are known as **wavefronts**. The separation of the wavefronts is equal to the wavelength of the ripples. Figure 14.14c also shows lines (the red arrows) to indicate how the direction of travel of the ripples changes. This diagram may remind you of the ray diagram for the law of reflection of light (see Figure 14.5).

Looking at the red arrows, you can see that the waves obey the same law of reflection as light:

angle of incidence = angle of reflection

wavefront: a line joining adjacent points on a wave that are all in step with each other

Refraction of ripples

Refraction of light occurs when the speed of light changes. We can see the same effect for ripples in a ripple tank (Figure 14.15). A glass plate is immersed in the water, to make the water shallower in that part of the tank. There, the ripples move more slowly because they drag on the bottom of the tank (which is now actually the upper surface of the submerged glass plate).

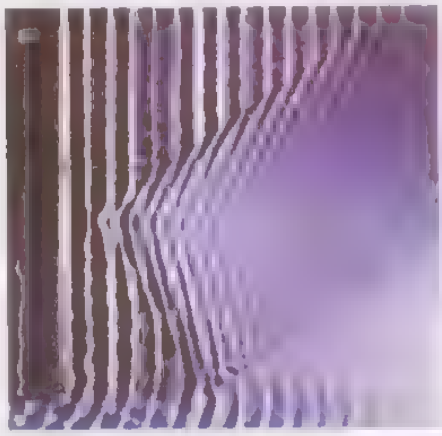


Figure 14.15a: The refraction of plane waves by a flat glass plate in a ripple tank. A submerged glass plate makes the water shallower in the grey region; in this region, the ripples move more slowly, so that they lag behind the ripples in the deeper water.

b

Figure 14.15b: This wavefront diagram shows the same pattern of ripples as **a**. The rays show that the refracted ray is closer to the normal, just as when light slows down on entering glass

In the photograph in Figure 14.15a, you can see that these ripples lag behind the faster-moving ripples in the deeper water. Their direction of travel has changed. Figure 14.15b shows the same effect, but as a wavefront diagram. On the left, the ripples are in deeper water and they move faster. They advance steadily forwards. On the right, the ripples are moving more slowly. The right-hand end of a ripple is the first part to enter the shallower water, so it has spent longest time moving at a slow speed. This means that the right-hand end of each ripple lags behind.

The rays (the red arrows) marked on Figure 14.15b show the direction in which the ripples are moving. They are always at right angles to the ripples. They emphasise how the ripples turn so their direction is closer to the normal as they slow down, just as we saw with the refraction of light in Chapter 13.

Diffraction

Figure 14.16: The waves on the sea are straight. As they pass through the gap in the rocks, they start to spread out

An interesting thing happens to waves when they go through a gap in a barrier. Figure 14.16 shows what happens. Waves passing through the gap in the rocks spread out to fill the bay. This is an example of a phenomenon called **diffraction**. Figure 14.17 shows water waves in a ripple tank being diffracted as they pass through a gap

[illegible]

diffraction: when a wave spreads out as it travels through a gap or past the edge of an object

Figure 14.17: Ripples are diffracted as they pass through a gap in a barrier – they spread into the space behind the barrier

Sound waves are diffracted as they pass through doorways and open windows. This is why we can hear a person around the corner, even though we cannot see them. This supports the idea that sound travels as a wave.

Light waves are also diffracted when they pass through very tiny gaps. You might notice that, on a foggy night, street lamps and car headlights appear to be surrounded by a halo of light. This is because their light is diffracted by the tiny droplets of water in the air. The same effect can also sometimes be seen around the Sun during the day (see Figure 14.18).

Figure 14.18: Light from the Sun is diffracted as it passes through foggy air (which is full of tiny droplets of water), producing a halo of light.

EXPERIMENTAL SKILLS

Studying waves in a ripple tank

In this experiment you will observe reflection and refraction of ripples in a ripple tank and describe the reflection, refraction and diffraction of water waves

You will need:

- ripple tank and dipper with an eccentric motor
- power supply
- light
- metal or plastic barriers
- glass sheet to adjust the depth of water

Safety: It is easiest to observe the shadow of the waves in a darkened room. Keep the work area tidy to avoid trip hazards. Clear up any spilt water immediately.

Getting started

What effect does changing the speed of the motor have on the wavefronts produced?

If you put a small piece of cork in the water, how does it move?

Method

1. Adjust the motor so that you can clearly see the shadows of the waves moving across the tank.
2. Place a barrier in the tank at an angle so that it reflects the waves.
3. Look carefully at the reflected waves. Investigate what happens when you change the angle of the barrier.
4. Place the glass sheet in the tank so that the waves hit it straight on. Adjust the water level so that the water above the glass is very shallow.
5. Observe the waves as they enter and leave the shallower water.
6. Investigate the effect of turning the glass sheet so that the waves enter the shallow water at an angle.
7. Use two barriers to create a wide gap for the waves to pass through. Observe the effect.
8. Narrow the gap until it is about the same size as the wavelength of the waves. Observe how this affects the waves.

Questions

1. Draw a diagram to show what happens to plane waves when they strike a flat reflector placed at 45° to their direction of travel.
2. Draw a diagram to show what happens to plane waves when:
   a. they enter the shallower water straight on
   b. they enter shallower water at an angle.
3. Draw diagrams to show diffraction at a wide gap and at a narrow gap.
4. How can the speed of ripples in a ripple tank be changed?

Compare your ripple tank diagrams to another student's. Think about what makes a good diagram. Are your diagrams clear, simple and correctly labelled? Add notes to your diagrams saying what you have done well and what could be improved.

ACTIVITY 14.1

Learning the definitions of key words

You will have noticed that this topic contains a lot of key words. To explain waves you need to be familiar with these words, which describe wave characteristics and how waves behave.

Design and make a revision activity to help you remember the key definitions. You could use one of the ideas below or create your own.

- Flash cards: have a key word on one side and its definition on the other. This way, anything you get wrong, you will see the correct answer straight away which will help for the next time.
- Questions: write a set of short questions such as, 'What is the unit of frequency?' on a large sheet of paper. Give each question a mark (1 for easy, 2 for difficult). With a friend, take turns answering questions. Remove any which have been answered correctly as you go. The winner is the person with most points.
- Create self test questions on a quiz app. This way you can test yourself regularly and quickly.

REFLECTION

Learning key words is important in physics as words have very precise meanings which may be different from the everyday use of the word. Think about how you learn these words. What activities are most helpful for you? Are you regularly checking back over key words from other chapters? Have you learnt revision techniques in other subjects which you can apply here?

Questions

14 The red lines in Figure 14.19 show sound waves created by person A.

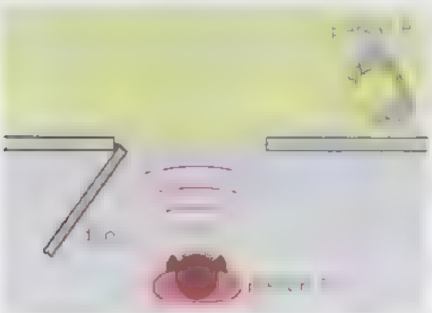


Figure 14.19

a Copy and complete Figure 14.19 to show how the sound waves reach person B.

b What type of waves are sound waves?

15 Figure 14.20 shows four ripples, a–d, in a ripple tank. Copy and complete each diagram to show what happens to the ripples. Label each diagram with the wave phenomenon it is showing.

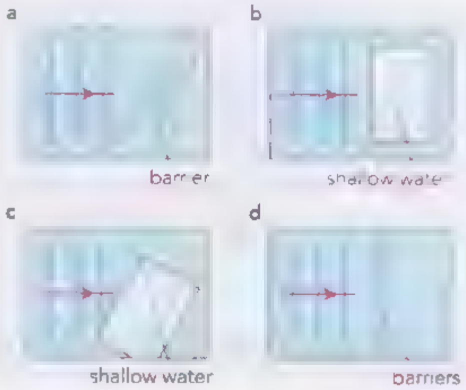


Figure 14.20

Diffraction, more or less

Waves are diffracted when they pass through a gap or around the edge of an obstacle. The size of the gap affects diffraction. The effect is greatest when the width of the gap is equal to the wavelength of the ripples (Figure 14.21).

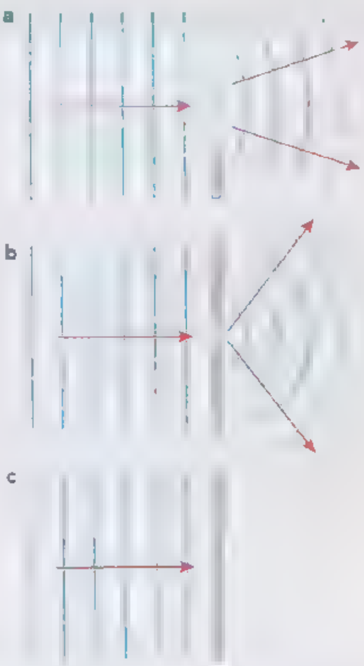


Figure 14.21: Diffraction is greatest when the width of the gap is equal to the wavelength of the waves being diffracted. When the gap is much smaller than the wavelength, the waves do not pass through at all.

Compare Figure 14.22 with Figure 14.17. In Figure 14.22, the gap is wider, so it is now much bigger than the wavelength of the waves. The diffraction effect is not so pronounced. The central part of the ripple remains straight after it has passed through the gap. At the edges, the ripples are curved.

Figure 14.22: The wavelength of the waves is much smaller than the gap, so the waves are diffracted less.

Sound waves have wavelengths between about 10 mm and 10 metres. This is why they are diffracted as they pass through doorways and windows. Light waves have a much shorter wavelength – less than a millionth of a metre. This is why very small gaps are needed to see light being diffracted.

Diffraction also happens as waves pass an edge. The greater the wavelength of the waves, the greater the angle at which they are diffracted (Figure 14.23).

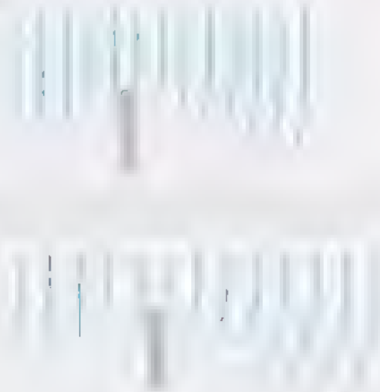


Figure 14.23: Increasing the wavelength of waves increases the angle of diffraction.

Questions

16 Explain why person B in question 14.14 can hear person A, but not see them.

17 A man who lives behind a mountain [illegible] receive waves with a wavelength of 1500 metres, but not shorter waves with a wavelength of 2 metres. Explain why.

18 Draw a diagram to show how a series of parallel, straight wavefronts are altered as they pass through a gap with a width that is equal to the wavelength of the waves.

So what is a wave?

You work for a television company that is making a programme about the discovery of gravitational waves. The producer has asked your team to work on a five minute introduction to the general idea of waves. You need to answer the question: 'What is a wave?'.

The director thinks viewers may think of waves as being just water waves. She wants viewers to have a clear idea of what a wave is and how waves behave. Viewers should understand why physicists describe light and sound as waves.

You will need to show that water, light and sound waves behave in the same ways, particularly that they can be reflected, refracted and diffracted.

You should also explain some of the differences, for example, that sound waves need a medium.

Your section will introduce the programme so it needs to get the audience's interest so they don't reach for the remote control. (You could point out that the remote control is operated by infrared or radio waves!) The producer suggests you might show a crowd doing a Mexican wave as a way of showing energy being transferred by a wave. You could also include pictures or video clips of water waves, including seismic waves and tsunamis.

Once you have the audience interested, you will need to introduce the idea that waves transmit energy but not matter. Illustrate this by referring to waves in springs, boats bobbing on the waves at sea, or any other examples you can think of. You should then cover wave behaviour, giving as many examples as possible to show the audience how many everyday things depend on waves.

You may present your ideas as a video, or as a storyboard.

When the programme is broadcast all your names will be in the credits, along with your job title. Decide early on what each person will do. Jobs could include: researcher, picture researcher, editor, producer, sound technician, cameraperson and any other roles you think are needed.

Waves transfer energy without transferring matter.
Waves can be clearly seen in water and springs.
Waves can be transverse or longitudinal
Wave speed, frequency and wavelength are related by the equation $v = f\lambda$.
Waves can be reflected and refracted
Waves can be diffracted when they pass through a gap or round an obstacle.
The wave model can be used to explain reflection, refraction and diffraction.

[illegible]

1 Which describes what is transferred by a wave? [1]

A energy and matter

B just energy

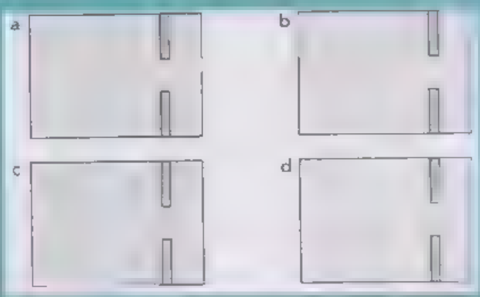
C just matter

D neither energy nor matter

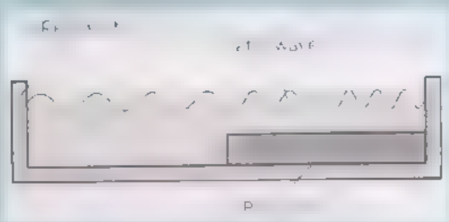
2 Which line gives the correct units for the wave measurements listed? [1]

	Wavelength	Frequency	Wave speed
A	metres	metres	metres per second
B	metres per second	hertz	metres
C	metres	hertz	metres per second
D	metres	metres per second	hertz

3 [illegible]



4 The diagram shows waves going from deep water into shallower water above a Perspex block.



Describe what happens to each of the following when the wave enters the shallower water.

a wavelength [1]

b wave speed [1]

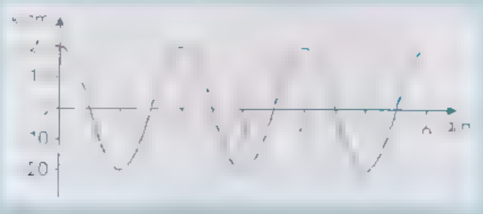
c frequency [1]

d [illegible] [1]

[Total: 4]

describe: state the points of a topic; give characteristics and main features

5 This diagram shows a wave on the sea.



a What is the wavelength of the wave? [1]

b A student says the amplitude is 40 cm. [illegible] what mistake they have made and write down the correct amplitude. [1]

c Later in the day the sea is calmer. The amplitude is reduced to 10 cm. On graph paper, draw the new wave. [1]

d A bird is floating on the sea. Describe the movement of the bird as the waves pass it. [2]

e The student observes the waves closer to the beach. The wavelength here is 0.5 metres. What can you [illegible] from this? [1]

[Total: 6]

6 Radio station A broadcasts radio waves with a wavelength of 1500 metres and a frequency of 200 kHz. Station B has a frequency of 100 MHz.

a [illegible] the speed at which the waves travel. [1]

b Use your answer to part **a** to calculate the wavelength of the waves from station B. [1]

[Total: 4]

7 A vibration generator is used to make a wave on a string.

a What is the name of the distance labelled a? [1]

b The distance from the pulley to the vibration generator is [illegible]. What is the wavelength of the wave? [1]

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

deduce: conclude from available information

calculate: work out from given facts, figures or information

CONTINUED

c The frequency of the vibrations from the generator is 60 Hz.
Calculate the speed of the waves in the string. **[2]**

d The vibration of the string causes a sound wave to pass through the air.
What type of wave is:

i the wave in the string? **[1]**

ii the sound wave in the air? **[1]**

[Total: 6]

8 A student investigates waves in a ripple tank. All the water is the same depth.

She measures the wavelength of each wave as 22 cm. The period of each wave is 0.58 s.

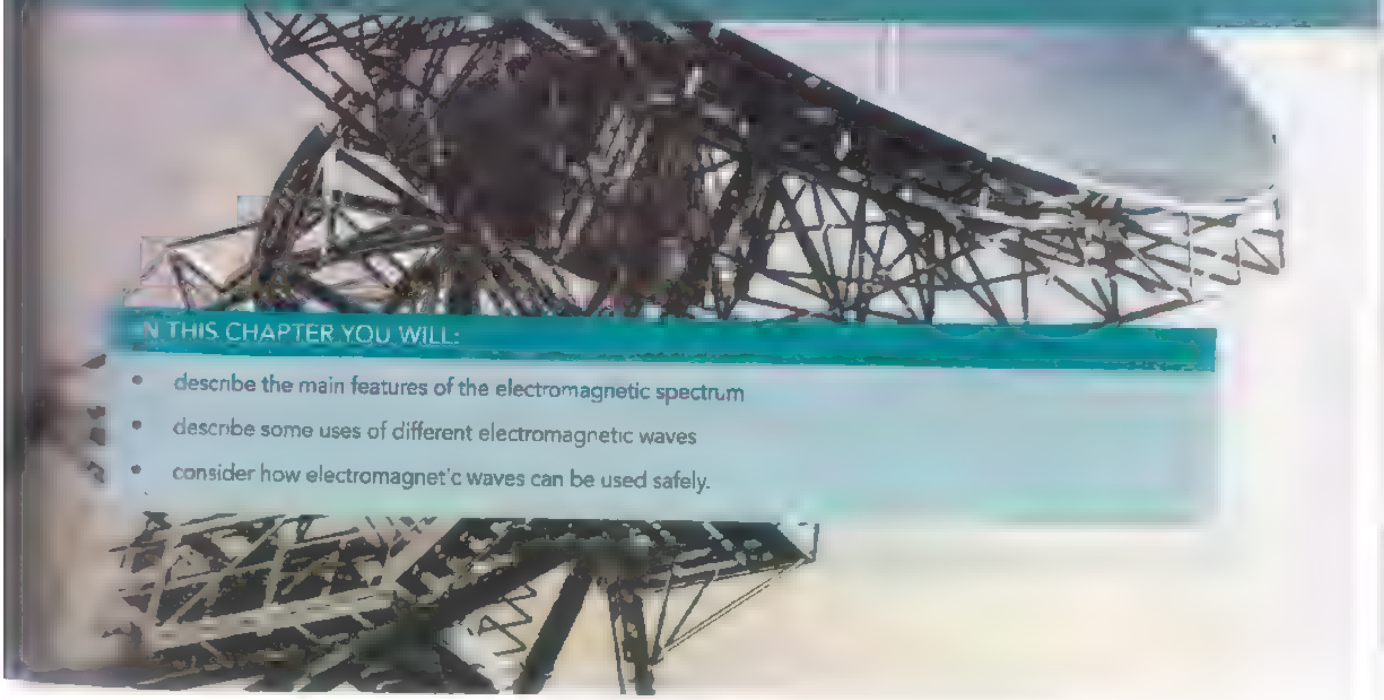
Calculate the speed of the wave. **[4]**

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
State what is transferred by a wave	14.1			
Recall that waves (including electromagnetic and seismic waves), vibrations in springs and ropes, light, and sound are all examples of wave motion.	14.1			
Illustrate wave motion using ropes, springs and water waves.	14.1			
Define and use the terms: wavefront, wavelength, frequency, amplitude, wave speed, crest, trough, compression, rarefaction.	14.1			
Recall and use the equation linking wave speed, frequency and wavelength	14.2			
Recall the direction of vibrations in transverse and longitudinal waves.	14.1			
Give examples of transverse and longitudinal waves.	14.1			
Draw diagrams to show reflection, refraction and diffraction of waves.	14.3			
Describe how the wavelength of a wave affects diffraction	14.3			

Chapter 15

The electromagnetic spectrum



IN THIS CHAPTER YOU WILL:

- describe the main features of the electromagnetic spectrum
- describe some uses of different electromagnetic waves
- consider how electromagnetic waves can be used safely.

Think about what you have learnt so far about waves.

Write down five bullet points which sum up what you know about waves – including light and sound.

Pair up and agree five points from your combined lists. You can change or combine them.

Join with another pair and write out five points that the group agrees on. Display these points to the class.

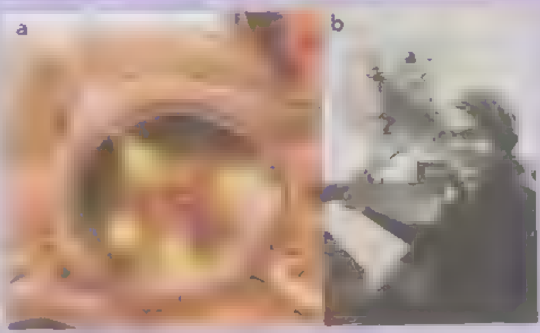


Figure 15.1a: This artist's impression shows how high energy gamma radiation can be finely targeted to kill tumour cells. **b:** Jocelyn Joyce Burnell was one of the first astrophysicists to observe light from pulsars. Pulsars emit pulses of light at very regular intervals, making them enormously accurate clocks. Pulsars can be used to measure astronomical distances very accurately.

The light waves we see are part of a bigger family of waves called the electromagnetic spectrum. These range from gamma rays (seen killing a cancer cell in Figure 15.1a) to the radio waves used in radio astronomy by astronomers such as Jocelyn Joyce Burnell (Figure 15.1b). In this chapter you will learn about these waves: what they have in common and the differences that make them useful in a huge variety of ways.

All these forms of radiation have useful applications, but many can also cause harm.

Ultraviolet radiation from the Sun can cause skin cancer. However, in trying to avoid skin cancer by staying indoors and covering skin whilst outside, we risk vitamin D deficiency. Our bodies create vitamin D when exposed to sunlight. Lack of it can cause a range of health problems, including rickets.

Gamma radiation released in nuclear disasters has been shown to cause cancers, and yet when used correctly, the same radiation can be directed on to cancer cells to kill them.

Decisions about the use of potentially harmful radiation have to balance risk with benefit. Consider a pregnant woman involved in a car crash who appears to have sustained a serious spinal injury. X-rays could damage the developing fetus, but without X-ray images to inform treatment, the woman could be paralysed.

Decisions like this have no easy answers. Whichever decision is made, the doctors will aim to minimise risk; for example, if they decide to use X-rays, they will shield the fetus with lead shields which block X-rays as much as they can.

As you will see in this chapter, electromagnetic radiation is all around us. Decisions about how to use these waves have to be taken by everybody, not just the scientists.

Discussion questions

A large sports arena concerned about security is considering installing X-ray scanners to check supporters and their bags for dangerous items.

1 Discuss the risks and benefits of installing this system.

2 Consider who should make the final decision: the arena managers, supporters or scientists?

15.1 Electromagnetic waves

William Herschel was an astronomer. In 1799 he was investigating the spectrum of light from the Sun. He used a prism to create a spectrum then placed a thermometer at different parts of the spectrum. The thermometer reading increased when the light fell on it. The light energy was absorbed, creating a heating effect. Herschel noticed this effect was greatest for red light and smallest for violet.

Herschel then placed his thermometer past the red end of the spectrum. The temperature rise was even greater. He concluded that there must be some type of radiation, invisible to the human eye, beyond the red end of the spectrum. He called this infrared radiation ('infra' means below). Infrared radiation is the thermal radiation described in Chapter 11. It is the heat you can feel radiating out from any hot object.

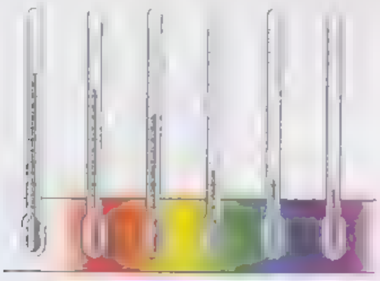


Figure 15.2: A modern version of Herschel's experiment. The spectrum of light from the Sun extends beyond the visible region, from infrared to ultraviolet. The thermometer placed beyond the red light detects more thermal radiation than any of the others.

Beyond the violet end of the spectrum

The discovery of radiation beyond the red end of the spectrum encouraged people to look beyond the violet end. In 1801, a German scientist called Johan Ritter used silver chloride to look for 'invisible rays'. Silver salts are blackened by exposure to sunlight (this is the basis of film photography). Ritter directed a spectrum of sunlight onto paper soaked in silver chloride solution. The paper became blackened and, to his surprise, the effect was strongest beyond the violet end of the visible spectrum. He had discovered **ultraviolet radiation** ('ultra' means beyond).

Both infrared and ultraviolet radiation were discovered by looking at the spectrum of light from the Sun. However, they do not have to be produced by an object like the Sun. Imagine a lump of iron that you heat in a Bunsen flame. At first, it looks dull and black. Take it from the flame and you will find that it is emitting infrared radiation. Put it back in the flame and heat it more. It begins to glow, first a dull red colour, then more yellow, and eventually white hot. It is emitting visible light. When its temperature reaches about 1000 °C, it will also be emitting ultraviolet radiation.

This experiment suggests that there is a connection between infrared, visible and ultraviolet radiation. A cool object emits only radiation at the cool end of the spectrum. The hotter the object, the more radiation it emits from the hotter end.

The Sun is a very hot object (Figure 15.3). Its surface temperature is about 5500 °C, so it emits a lot of ultraviolet radiation. Most of this is absorbed in the atmosphere, particularly by the ozone layer. A small amount of ultraviolet radiation does get through to us. The ozone layer is depleted (decreased) by chemicals used in aerosols and refrigerants. Depletion lets more ultraviolet through, increasing the risk of skin cancer. In 1985, an international agreement called the Montreal Protocol regulated, then banned, the use of CFCs – the main chemicals involved in the depletion. In 2019, NASA reported a 20% decrease in ozone depletion. While there is still work to be done, this is an example of what global cooperation on climate issues can achieve.

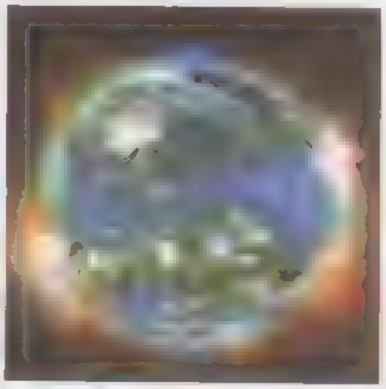


Figure 15.3: The Sun is examined by several satellite observatories. This image was produced by the SOHO satellite using a camera that detects the ultraviolet radiation given off by the Sun. You can see some detail of the Sun's surface, including giant prominences looping out into space. The different colours indicate variations in the temperature across the Sun's surface.

Electromagnetic waves

We have seen that a spectrum is formed when light passes through a prism because some colours are refracted more than others. The violet end of the spectrum is refracted the most. Now we can deduce that ultraviolet radiation is refracted even more than violet light, and that infrared radiation is refracted less than red light.

To explain the spectrum, and other features of light, physicists developed the wave model of light.

Just as sound can be thought of as vibrations or waves travelling through the air (or any other material), so we can think of light as being another form of wave. Sounds can have different pitches – the higher the frequency, the higher the pitch. We can think of a piano keyboard as being a 'spectrum' of sounds of different frequencies. Light can have different colours, according to its frequency. Red light has a lower frequency than violet light. Visible light occurs as a spectrum of colours, depending on its frequency.

A Scottish physicist, James Clerk Maxwell, described light as small oscillations in electric and magnetic fields which he called electromagnetic waves. His theory allowed him to predict that they could have any value of frequency. In other words, beyond the infrared and ultraviolet regions of the spectrum, there must be even more types of electromagnetic wave (or electromagnetic radiation). By the early years of the 20th century, physicists had discovered or artificially produced several other types of electromagnetic wave to complete the **electromagnetic spectrum**.

The electromagnetic spectrum is a family of transverse waves. Like all waves, they can be reflected, refracted or diffracted. They all travel at the same speed as light in a vacuum. The waves have different frequencies, and this means they have different effects on the materials with which they interact. These waves have many very important uses, and some can be hazardous.

The speed of electromagnetic waves

All types of electromagnetic wave have one thing in common: they travel at the same speed in a vacuum. They travel at the speed of light, which has a value close to 300 000 000 m/s (3×10^8 m/s) in a vacuum and approximately the same speed in air. Like light, the speed of electromagnetic waves depends on the material through which they are travelling.

Wavelength and frequency

We can represent light as a transverse wave. Figure 15.4 compares red light with violet light. Red light has a greater wavelength than violet light. This means that there is a greater distance from one wave crest to the next. This is because both red light and violet light travel at the same speed, but violet light has a greater frequency, so it goes up and down more often in the same length.

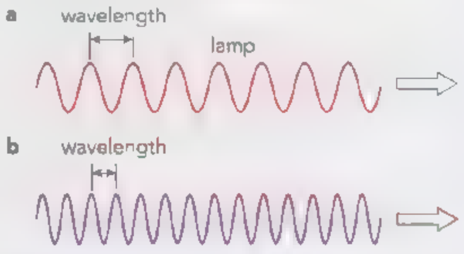


Figure 15.4: Comparing red and violet light waves. Both travel at the same speed, but red light has a longer wavelength because its frequency is lower. The wavelength is the distance from one crest to the next (or from one trough to the next). Think of red light waves as longer, lazy waves. Violet light is made up of shorter, more rapidly vibrating waves.

The waves that make up visible light have very high frequencies: over one hundred million million hertz, or 10^{14} Hz. Their wavelengths are very small, from 400 nm (nanometres) for violet light to 700 nm for red light. (1 nm is one-billionth or one-thousand-millionth of a metre, so 400 nm $= \frac{400}{1\,000\,000\,000}$ m.) More than one million waves of visible light fit into a metre.

Figure 15.5 shows the complete electromagnetic spectrum, with the wavelengths and frequencies of each region. In fact, we cannot be very precise about where each region starts and stops. This is similar to the light spectrum: it is hard to say where red finishes and orange begins. Even the ends of the visible light section are uncertain, because different people can see slightly different ranges of wavelengths, just as they can hear different ranges of sound frequencies.

ultraviolet radiation: electromagnetic radiation with a wavelength shorter than that of visible light

electromagnetic spectrum: the family of radiations similar to light

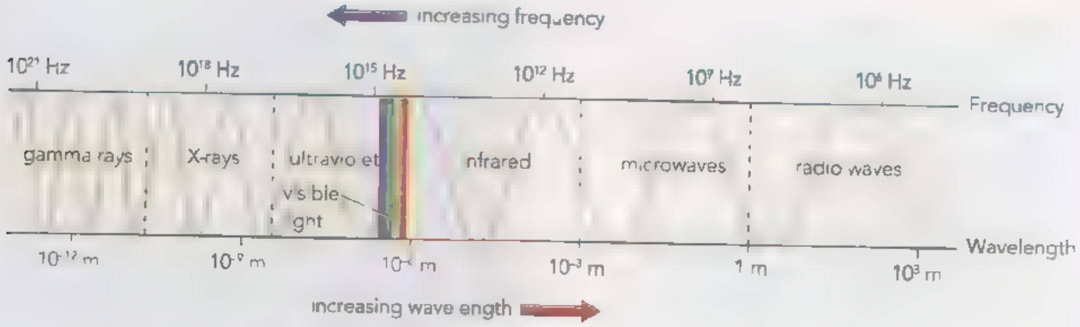


Figure 15.5: The electromagnetic spectrum. Remember all waves travel at the same speed and because $v = f\lambda$. As frequency increases, wavelength decreases.

Questions

1. Draw and label two waves to show the difference between red light and violet light.
2. Write the names of the waves in the electromagnetic spectrum:
   a in order of increasing wavelength
   b in order of increasing frequency.
3. Describe and explain what happens when monochromatic green light of wavelength 540 nm passes through a prism.
4. Use the equation $v = f\lambda$ to calculate the frequency of the green light in question 15.3.

Uses of electromagnetic waves

The different frequencies of the waves in the electromagnetic spectrum give them different properties and this means that they are useful in different ways. Here are some important examples.

Radio waves

Radio waves are used to broadcast radio and television signals. These waves are sent out from a transmitter a few kilometres away to be captured by an aerial on the roof of a house. Radio astronomy can be used to detect radio waves from objects such as stars, galaxies and black holes. Radio frequency identification (RFID) chips are microchips inserted underneath the skin. These can store vital medical information and could be used instead of a passport, or as a contactless bank card.

An RFID tag stores data. It transmits the data as radio waves, which is read by an electronic reader.

Figure 15.6: Tiny RFID tags can store and transmit data. A tag inserted in your body could be used to open doors or pay for shopping to track for your movements.

Microwaves

Used in satellite television broadcasting, because microwaves pass easily through the Earth's atmosphere. They travel up to a broadcasting satellite, thousands of kilometres away in space. Then they are sent back down to subscribers on Earth. Microwaves are also used to transmit mobile phone (cellphone) signals between masts, which may be up to 20 km apart

Microwaves ovens emit microwaves, which are absorbed by molecules in food, causing heating.

Infrared radiation

Infrared radiation is used in remote controls for devices such as televisions. A beam of radiation from the remote control carries a coded signal to the appliance, which changes the settings on the television; for example, changing channel, increasing the volume. You may be able to use a smartphone camera to observe this type of radiation, which would otherwise be invisible to our eyes. Point a remote control at your phone and record what happens as you press buttons. Grills and toasters also use infrared radiation to cook food. Security alarms send out beams of infrared radiation and detect changes in the reflected radiation, which may indicate the presence of an intruder. Infrared red light is also used together with optical fibres. In Figure 15.9b an endoscope allows the doctor to see inside the patient. Visible light is passed down an optical fibre to illuminate the lungs of this COVID-19 patient. Reflected light travels back up to the doctor's eye. Infrared radiation can also be used in medicine to detect heat which may indicate infection, or to speed up healing and reduce pain.

Visible light

Visible light provides us with information about the world, both directly through our eyes and via optical instruments such as cameras, telescopes and microscopes. Visible light is also vital for photosynthesis.

Figure 15.7: Microwaves allow signals to be transmitted around the curve of the earth's surface.

Figure 15.8: Using an infrared scanner allows a doctor to see a patient's veins. This means injections can be targetted much more precisely.

Figure 15.9a: This leaf has used visible light to grow. It is illuminated by the microscope lamp, and the reflected light is focused by the microscope lenses. **b:** An endoscope allows the doctors to see inside the patient. Visible light is passed down an optical fibre to illuminate the lungs of this COVID-19 patient. Reflected light travels back up to the doctor's eye

Ultraviolet (UV) light

UV light causes some chemicals to emit visible light. This includes body fluids such as sweat and saliva. Forensic scientists use this to find evidence at crime scenes which is invisible to the human eye.

Chemicals which glow in UV light can be used for security marking of valuable equipment and banknotes.

Ultraviolet light can be used to sterilise water. Exposure to UV radiation destroys DNA within any bacteria and viruses contained in the water. This makes the bacteria and viruses harmless and the water much safer to use.

Figure 15.10: Many banknotes have markings which are only visible in ultraviolet light. This helps in the detection of forged banknotes.

X-rays

X-rays can penetrate solid materials and so they are used in security scanners at airports. They are also used in hospitals and clinics to see inside patients without the need for surgery. The X-rays are detected using electronic detectors. Bone absorbs X-rays more strongly than flesh, so bones appear as a shadow in the image. Similarly, a metal gun will appear as a shadow because it absorbs X-rays more strongly than the items around it in Figure 15.11.

Figure 15.11: X-ray scanners allow airport security to quickly detect hidden items.

Gamma rays

Gamma rays can damage or kill living cells. A targeted beam of gamma rays can be used to kill cancerous cells.

Surgical instruments can be sterilised by using gamma rays to kill any bacteria.

Gamma rays can also be used in the detection of cancer. You will learn more about gamma rays and how they are used in Chapter 23.

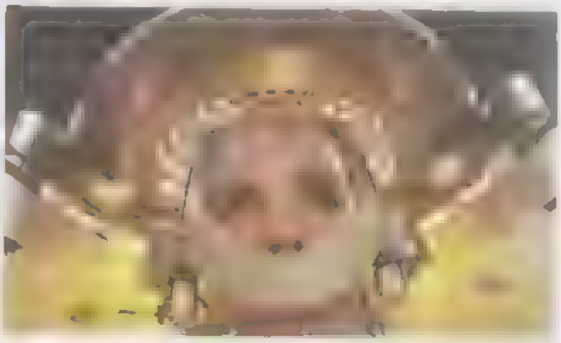


Figure 15.12: A nurse demonstrates a radiation helmet. The holes in the helmet allow the gamma rays to be targeted exactly on to a tumour.

Questions

5 Name two types of electromagnetic radiation that are used to cook food.

6 Name three types of electromagnetic radiation that have medical uses.

7 A girl phones her friend on her mobile phone while watching TV by a log fire. Explain how infrared radiation, microwaves, visible light and radio waves are involved in this.

15.2 Electromagnetic hazards

All types of radiation can be hazardous. Even bright light shining into your eyes can blind you. Infrared radiation can cause burns. UV radiation from the Sun can damage skin cells which may lead to sunburn and skin cancer. Sunbeds can also damage skin cells and should be used with care. UV radiation can also damage eye cells which is why is important to protect your eyes in bright sunlight by wearing sunglasses or a hat. In general, the higher the frequency of the wavelength, the greater the harm it can cause.

X-rays and gamma rays are the most dangerous part of the electromagnetic spectrum. They can cause cell mutations which may lead to cancer. People who work with X-rays and gamma rays are in danger of being exposed to too much radiation. They can protect themselves by standing well away when a patient is being examined, or by enclosing the equipment in a metal case, which will absorb rays.

Longer waves such as microwaves are much less harmful, but as we use them a lot more frequently in everyday life, we are exposed to much larger amounts of these waves. Microwaves are used to cook food in microwave ovens. This shows that they have a heating effect when absorbed. Telephone engineers, for example, must take care not to expose themselves to excessive amounts of microwaves when they are working on the masts of a mobile phone (cellphone) network. Domestic microwave ovens must be checked to ensure that no radiation is leaking out.

Mobile phones use radio waves and microwaves. Many people are concerned that these could be harmful. Scientists have researched this and the only effect they have found consistent evidence for is a slight heating effect. This is not believed to be harmful. If any risks are found, they would have more effect on children, as they are still developing. Any harm would be increased by using the phone for longer

Figure 15.13a: The radiographer operates the machine from a separate room

Figure 15.13b: All areas where X-rays or gamma rays are used have hazard warning labels.

Questions

8 The radiographer must leave the room before operating an X-ray machine. Why is it considered too dangerous for the radiographer but not for the patient?

9 A headline reads, 'Scientists prove mobile phones are safe'. Explain why this headline is misleading.

Electromagnetic waves – friend or foe?

Each of the pictures in Figure 15.14 represents a use or a danger of a type of electromagnetic radiation. Identify the wave involved and discuss what the use or danger is.

Figure 15.14: Uses and dangers of electromagnetic radiation

Find or draw as many pictures as you can showing the uses and dangers of electromagnetic waves.

Use your pictures to make a poster. Include a representation of the electromagnetic spectrum similar to Figure 15.5

15.3 Communicating using electromagnetic waves

Satellites

Satellites are objects which orbit the Earth. Earth has one natural satellite – the Moon. Earth also has many artificial satellites, many of which are used in the transmission of information carried by electromagnetic waves. Most artificial satellite communication uses microwaves.

Some of the satellites used for communication are in geostationary orbits. This means that they orbit at the same rate as the Earth turns and so they stay above one point on the Earth's surface. They are about 35 000 km above the Earth's surface and are positioned above the Equator. These satellites are powerful and can transmit large amounts of data. This makes them suitable for satellite television and some satellite phones. The waves travel a long distance to the satellite, meaning there is a slight delay, making it more difficult to have a conversation.

Low Earth orbits are much closer. They can be as low as 2000 km above the Earth's surface. This means there is no delay in conversation. These satellites orbit the Earth in as little as two hours. A lot more of these are needed than for geostationary orbits as they only cover a small area of the Earth's surface (see Figure 15.15). They cannot transmit data as fast as geostationary satellites and so are not suitable for television transmission.

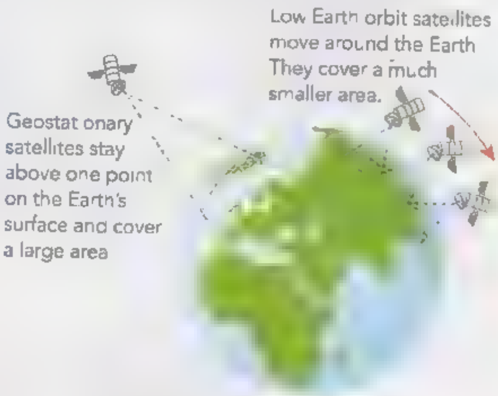


Figure 15.15: Low Earth orbits require many more satellites.

The right wave for the job

Mobile phones and wireless internet use microwaves, because they can pass through most walls and only a small aerial is needed

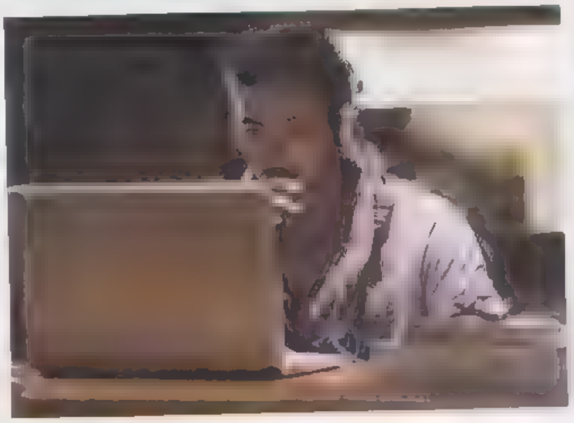


Figure 15.16 This laptop is connected to the internet using microwaves

Bluetooth [illegible] hands-free mobile phone systems.

Figure 15.17: A woman wearing a bluetooth headset

Optical fibres (for cable television and high speed internet) use infrared radiation and visible light. Optical fibres are made of glass which is transparent to light and infrared radiation. These waves have a high frequency and can carry more data. This is vital for high speed broadband connections.

Figure 15.18: Optical fibres.

Analogue and digital signals

In telephone communication, the signal being transmitted starts off as a sound wave. This varies in amplitude and frequency as the people talk. A sound wave is an **analogue signal** – it can vary continuously. In traditional telephones, the sound wave is converted [illegible] signal is transmitted via copper wires to a receiver [illegible]

A digital system is a sequence of pulses. **Digital signals** are either on or off. Digital systems using optical fibres give a much clearer signal. They are also faster and optical cables can carry much more data than a copper cables.

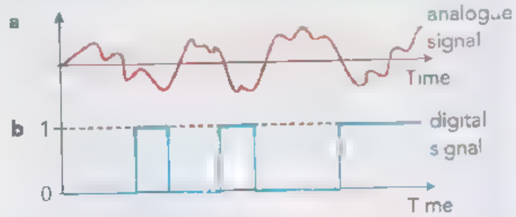


Figure 15.19: An analogue signal varies continuously while a digital signal is either on or off

analogue signal: a signal which varies continuously in frequency and amplitude

digital signal: a signal that consists of a series of pulses which are either on or off

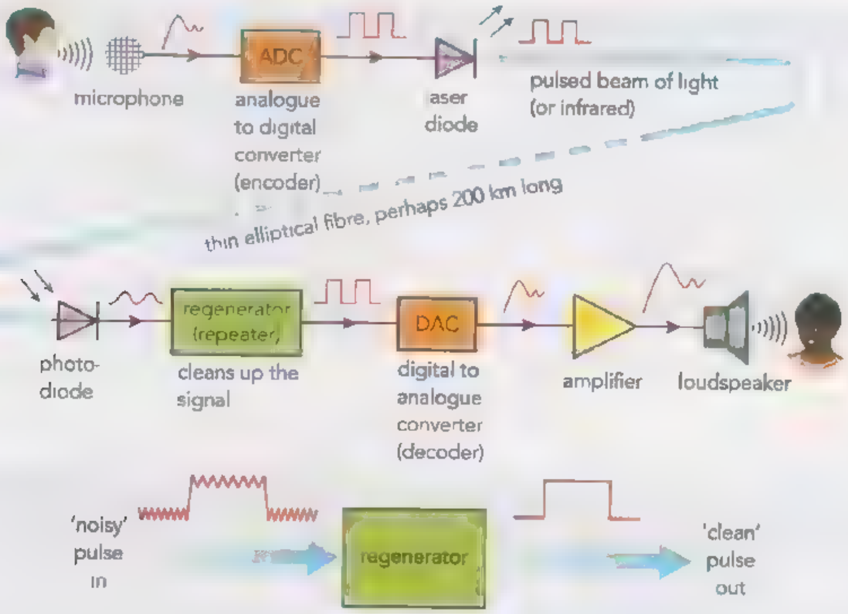


Figure 15.20: The use of regenerators means that digital signals can be transmitted over hundreds of kilometres without being distorted

Making a digital phone call

The analogue sound wave from a caller is encoded by a converter which turns the sound wave to a series of … The digital signal is carried along optical fibres … pulses or infrared waves. The signal passes … one or more regenerators which clean up the … removing any distortion. The regenerators also boost the signal if it has lost power. A second converter switches the signal back to an analogue signal which can be converted to a sound wave.

Digital signals can transmit data much more rapidly and accurately than analogue signals. Digital signals can also communicate directly with computers which only use digital data

… group of about four students. Write the different waves on identical cards (radio waves, microwaves, infrared, visible light, ultra violet, X-rays, gamma rays, red light, violet light, sound, ultrasound, water and seismic waves).

Place the cards face down in the middle. One player takes a card and looks at it without letting the others see. The other players then try to find out what the wave is by asking questions to which the answer can only be 'yes' or 'no'. Each player can only ask one question.

When the wave has been identified, the next player takes their turn.

There are two spectra which you need to remember in order: visib e light and the electromagnetic spectrum. How easily can you remember them? What helps you with this? Mnemonics can be very useful here. The colours of the visible spectrum can be remembered using **R**ichard **O**f **Y**ork **G**ave **B**attle **I**n **V**a n. The first letters of the words correspond to the first letters of the colours. Try to make a mnemonic to remember the order of the waves in the electromagnetic spectrum.

Questions

10 There are two types of communication satellite geostationary and low earth orbit. Explain which type.

- **a** is best suited to transmitting TV signals
- **b** gives the shortest delay for phone conversations
- **c** takes least time to orbit the Earth

11 State two benefits of converting a phone signal from analogue to digital

PROJECT

Rainbow balloon debate

Balloon debates usually involve discussing which person should be thrown out of an overloaded hot air balloon basket, so that it does not crash. Each passenger explains why they should stay and then a vote is taken. In this activity, the passengers are the different waves of the electromagnetic spectrum.

Seven different wavelengths of radiation are travelling in a hot air balloon.

- Radio waves
- Microwaves
- Infrared radiation
- Visible light
- Ultraviolet radiation
- X-rays
- Gamma rays

The balloon can only manage six waves, and so one of the waves must be thrown overboard, or the balloon will crash. As a class you wi l debate which wave should be sacrificed. Each wave will have a team who prepare to speak in favour of their wave and look at arguments why the other waves should go

You wi l need to divide the class into seven teams (you could have fewer teams and leave some waves out if necessary). Your teacher will ass gn each team a wave

You will need to prepare arguments why your given wave is so important that it must stay in the balloon. Think about what it is used for – medical or communication uses for example – and why losing this would be bad. Think about the harmfu aspects of your wave – you will have to answer questions about these, so be prepared to defend your wave.

You will also need to prepare questions for the other waves. Your aim is to make them seem either harmful or not particularly useful so that they are more ikely to be voted off.

Your teacher will te l you how long each team can speak for and how long the question portion will last.

PEER ASSESSMENT

After every team has spoken and has been questioned, you will all vote for which wave must go. To help with this, record your impressions of each group on a sheet similar to this.

Use your scoring and notes to decide how you will vote.

> *Group name* ______________
>
> *Wave* ______________
>
> *Initial speech* ☺ 😐 ☹
>
> *Answering questions* ☺ 😐 ☹
>
> *Notes*
>
> ______________
>
> ______________

[illegible]

The electromagnetic spectrum is a group of waves which have similar properties to light
In order of increasing frequency, the waves in the electromagnetic spectrum are: radiowaves, microwaves, infrared, visible light, ultraviolet, X-rays and gamma rays.
All electromagnetic waves travel at the same speed - the speed of light.
The speed of light is 300 000 000 m/s.
Electromagnetic waves have different wavelengths and this gives them different properties and makes them suitable for different uses.
High frequency electromagnetic radiation can be hazardous. It can damage cells and cause cells to mutate
Radio waves, microwaves, visible light and infrared are used in communication systems.
Signals can be analogue or digital. Digital signals transmit data more accurately and faster

EXAM-STYLE QUESTIONS

1 Which statement is correct when comparing gamma rays and microwaves? [1]

A Microwaves have a higher speed in air and the same frequency.
B Microwaves have a higher frequency and the same wavelength.
C Microwaves have a longer wavelength and the same speed.
D Microwaves have a higher frequency and the same speed.

2 This is part of the electromagnetic spectrum:

radiowaves	microwaves	P	visible light	ultraviolet	Q	gamma rays

Increasing R

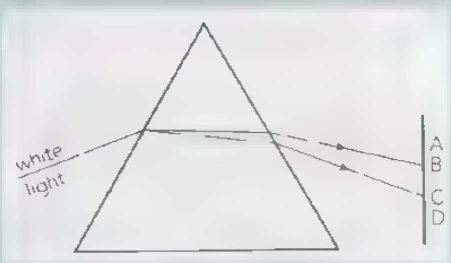
Which row correctly describes the labels P, Q and R? [1]

	P	Q	R
A	X-rays	infrared radiation	wavelength
B	infrared radiation	X-rays	frequency
C	X-rays	infrared radiation	frequency
D	infrared radiation	X-rays	wavelength

3 Which of the following statements is true for electromagnetic waves? [1]

A They all have the same frequency.
B They cannot be refracted.
C They all travel at the same speed.
D They are harmless.

4 This diagram shows white light being dispersed by a prism. The dispersed light hits a screen.



a What will be seen at B? [1]
b What will be seen at C? [1]

c What might be detected at A? [1]

d What might be detected at D? [1]

e [illegible] one way in which the waves at A, B, C and D are alike [1]

f State one way in which the four waves differ from each other [1]

[Total: 6]

5 These are some waves on the electromagnetic spectrum

	X rays		blue light	yellow light				

a Copy the diagram and add these labels in the correct order
radio waves, ultraviolet, infrared, gamma rays, microwaves, red light. [2]

b Name two of the waves which can be used for cooking [2]

c Name the wave with the highest frequency [1]

d Name two waves our senses can detect from the Sun [2]

[Total: 7]

[3]

[1]

[Total: 4]

state: express in clear terms

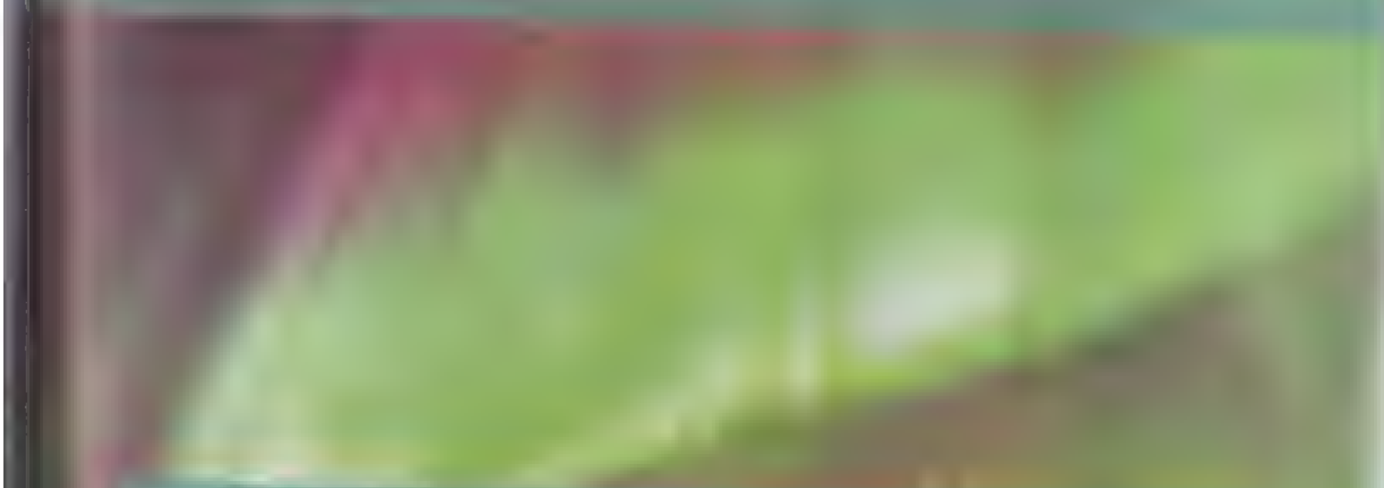
SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	Almost there	Confident to move on
State the speed of electromagnetic waves in a vacuum	15.1			
Describe the properties all electromagnetic waves share, including speed.	15.1			
List the waves in the electromagnetic spectrum in order of increasing frequency or wavelength.	15.1			
Describe how radio waves, microwaves, visible light and infrared are used in communications.	15.3			
Describe how X-rays are used in medicine and security.	15.2			
Describe how gamma rays can be harmful.	15.2			
Consider the safety issues which may arise when using microwaves.	15.2			
Describe the advantages of using digital signals.	15.3			

› Chapter 16

Magnetism



- ... be magnetic forces between magnets, and between magnets and magnetic materials
- ... sh between hard and soft magnetic materials, and non-magnetic materials
- ... be an experiment to identify the pattern of magnetic field lines around a bar magnet
- ... sh between the design and use of permanent magnets and electromagnets

Spend two minutes producing a mind map that answers the following questions before comparing notes with your neighbour for a further two minutes, adding or correcting your own work. Be prepared to share your thoughts with the class.

- Which elements are magnetic?
- Describe what life on Earth would be like if magnetism did not exist. This might include inventions that depend on magnetism.

FLIPPING FIELDS

A German polar researcher called Alfred Wegener (Figure 16.1) suggested that continents like South America and Africa used to fit together like a jigsaw and the pieces have drifted apart. Few people believed him but later scientists proved him right. Changes in the Earth's magnetic field helped prove the Earth's surface is made of plates that move in a process called plate tectonics.

Figure 16.1: Alfred Wegener, the man whose theory of continental drift was proved right by physics

The Earth has a magnetic field, as if a giant bar magnet sits along its axis (Figure 16.2). But where does this field come from? The Earth's core is made of iron. Like all metals, iron contains delocalised electrons, which are free to move. The spin of the Earth, and convection currents in the outer core move these electrons, which creates electric currents. These electric currents create magnetic fields just as in electromagnets, which you will meet later in the chapter. While many animals use the Earth's magnetic field for navigation, we have mostly replaced the compass with the GPS.

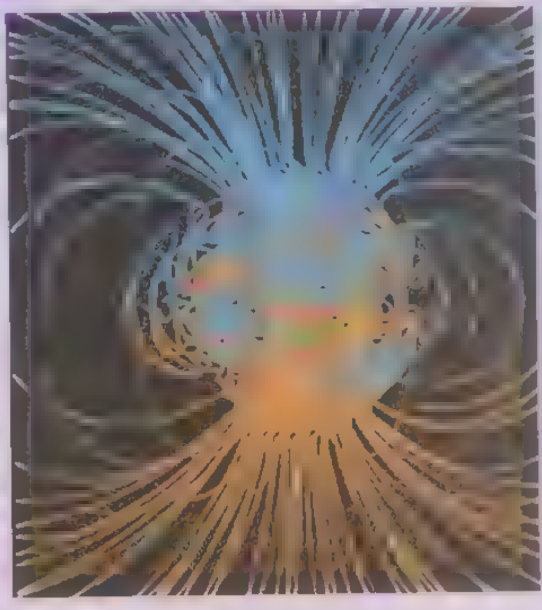


Figure 16.2: A NASA image of what the Earth's magnetic field looks like

Molten (liquid) rock erupting at mid-ocean ridges pushes the tectonic plates apart at about the same speed as our fingernails grow (Figure 16.3). Grains of magnetite in the molten rock act like little compasses, which are free to change direction. As the rock cools, these little compasses line up with the Earth's magnetic field and become fixed in place when the rocks crystallise (freeze). They show that the Earth's magnetic field has reversed in the past. The magnetic pattern is symmetrical (a mirror image on each side of the mid-ocean ridge), which shows that the continents were once stuck together, proving Wegener right.

The Earth's magnetic field acts as a shield, protecting our atmosphere and life on Earth by deflecting the harmful solar wind (a stream of charged particles from the Sun). It also protects all the electric circuits developed over the last century. In the process of reversing, the field has to decrease before increasing again in the opposite direction. Some scientists believe that animal species can become extinct during this reversal process, which has happened roughly once every 300 000 years in the last 20 million years. The last reversal was 780 000 years ago.

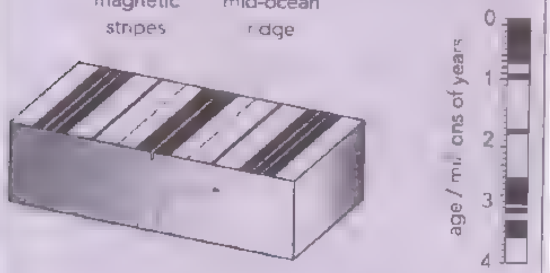


Figure 16.3: The magnetic stripes on the ocean floor that show that the Earth's magnetic field has reversed once every 300 000 years on average

Discussion questions

1. Describe what causes the Earth's magnetism in less than 20 words.
2. In what ways is the Earth's magnetic field beneficial?
3. Should we be concerned about magnetic reversals?

16.1 Permanent magnets

A compass needle is like a **bar magnet**. When it is free to rotate (Figure 16.4), it turns to point north–south. ...d points north – this is the magnet's north pole, pointing roughly in the direction of the Earth's geographical North Pole. The other end is the magnet's south pole. Sometimes, the north and south poles of a magnet are called the north-seeking pole and south-seeking pole, respectively

bar magnet: a rectangular-shaped permanent magnet with a north pole at one end and a south pole at the other

When two magnets are brought close together, there is a force between them. The north pole (N pole) of one will attract the south pole (S pole) of the other. Two north poles will repel each other, and two south poles will repel each other (Figure 16.5). This is summarised as:

- like poles repel
- unlike poles attract.

'Like poles' means poles that are the same – both north, or both south. 'Unlike poles' means opposite poles – one north and the other south. People often remember this rule more simply as 'opposites attract'.

Figure 16.4: A freely suspended magnet turns so that it points north–south.

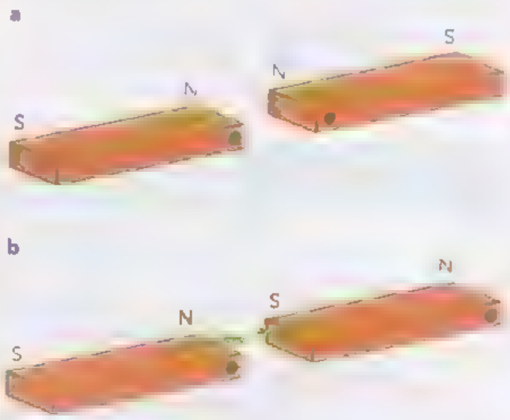


Figure 16.5a: Two like magnetic poles repel one another. **b:** Two unlike magnetic poles attract each other.

Since the north pole of the compass needle is attracted to the Earth's North Pole, it follows that there must be a magnetic south pole up there, under the Arctic ice. It is easy to get confused about this. In fact, for a long time, mediaeval scientists thought that compass needles were attracted to the Pole Star. Eventually, an English instrument-maker called Robert Norman noticed that, if he balanced a compass needle very carefully at its midpoint, it tilted downwards slightly, pointing into the Earth. Now we know that the Earth itself is magnetised, rather as if there was a giant bar magnet inside it.

Magnetic materials

Magnetic materials are attracted by a magnet and can be magnetised. Though they can be magnetised, not all pieces of magnetic material are magnets. They first need to be magnetised. In contrast, non-magnetic materials are not attracted by a magnet and cannot be magnetised. Examples include plastic and rubber.

A compass needle is a **permanent magnet**. Like many bar magnets, it is made of hard steel. You have probably come across another type of magnetic material, called ferrite. This is a ceramic material used for making fridge magnets and the magnets sometimes used to keep cupboard doors shut. There are also small rare-earth magnets in the headphones used with mobile phones, which are based on elements such as neodymium.

Most magnetic materials (including steel and ferrite) contain iron, the most common magnetic element. For this reason, they are known as ferrous materials (from the Latin word *ferrum* meaning 'iron'). Other magnetic elements include cobalt and nickel. (If a material contains iron, this is not a guarantee that it will be magnetic. Stainless steel contains a lot of iron, but magnets will not always stick to it.)

Magnetic materials may be classified as **hard** (permanent) or **soft** (temporary). Table 16.1 summarises the difference. A soft magnetic material such as soft iron can be magnetised and demagnetised easily.

[illegible]

permanent magnet: magnetised magnetic material that produces its own magnetic field that does not get weaker with time

hard (material): a material that, once magnetised, is difficult to demagnetise

soft (material): a material that, once magnetised, is easy to demagnetise

Induced magnetism

A bar magnet is an example of a permanent magnet. It can remain **magnetised**. Its magnetism does not disappear. Permanent magnets are made of hard magnetic materials.

A permanent magnet can attract or repel another permanent magnet. It can also attract other **unmagnetised** magnetic materials. For example, a bar magnet can attract steel pins or paper clips, and a fridge magnet can stick to the steel door of the fridge.

What is going on here? Steel pins are made of a magnetic material. When the north pole of a permanent magnet is brought close to a pin, the pin is attracted (see Figure 16.6). The attraction tells us that the end of the pin nearest the magnetic pole must be a magnetic south pole, as shown in Figure 16.6. This is known as **induced magnetism**. The two objects will have opposite polarities. In this example the pin will have a south pole induced in

Type of magnetic material	Description	Examples	Uses
hard	retains magnetism well, but difficult to magnetise in the first place	hard steel	permanent magnets, compass needles, loudspeaker magnets
soft	easy to magnetise, but readily loses its magnetism	soft iron	cores for electromagnets (discussed later in the chapter), transformers and radio aerials

Table 16.1: Hard and soft magnetic materials. Hard steel is both hard to bend and difficult to magnetise and demagnetise. Soft iron is both easier to bend and easier to magnetise and demagnetise.

the end nearest the north pole of a bar magnet. When the permanent magnet is removed, the pin will return to its unmagnetised state (or it may retain a small amount of magnetism).

magnetised: when a magnetic material has been made magnetic

unmagnetised: when a magnetic material has not been made magnetic

induced magnetism: when a magnetic material is only magnetised when placed in a magnetic field (for example, when brought close to the pole of a permanent magnet)

Figure 16.6: A steel pin is temporarily magnetised when a permanent magnet is brought close to it

Questions

1 Name three magnetic elements.

2 What is the rule about whether magnetic poles repel or attract?

3 Copy and complete Table 16.2.

Type of magnetic material	Description	Examples	Uses
Hard			
Soft			

Table 16.2

4 Why is a permanent magnet made of steel rather than iron?

16.2 Magnetic fields

A magnet affects any piece of magnetic material that is nearby. We say that there is a **magnetic field** around the magnet. You have probably done experiments with iron filings or small compasses to illustrate the magnetic field of a magnet. Figure 16.7 shows the field of a bar magnet as revealed by iron filings.

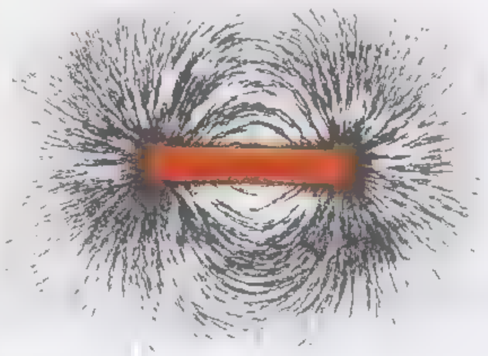


Figure 16.7: The magnetic field pattern of a bar magnet is illustrated by iron filings. The iron filings cluster most strongly around the two poles of the magnet. This is where the field is strongest.

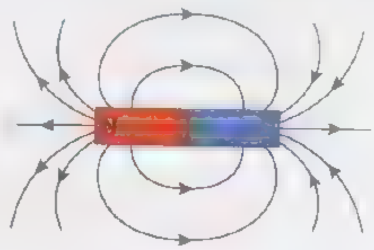


Figure 16.8: Field lines are used to represent the magnetic field around a bar magnet

Figure 16.8 shows how we represent the magnetic field of a single bar magnet using **magnetic field lines**. Of course, the field fills all the space around the magnet, but we can only draw a selection of typical lines to represent it. The pattern tells us two things about the field:

- Direction: the direction of a magnetic field line at any point is the direction of the force on the north pole of a magnet at that point. We use a convention

that says that field lines come out of north poles and go in to south poles.

- Strength: lines that are close together indicate a strong field.

magnetic field: a region of space around a magnet or electric current in which a magnetic pole experiences (feels) a force

magnetic field lines: represent the direction the magnetic force would have on the north pole of a magnet

plotting compass: very small compass with a needle that lines up with magnetic field lines, allowing changes in field direction to be observed and plotted over a very short distance

Plotting field lines

Iron filings can illustrate the pattern of the magnetic field around a magnet. Place a magnet under a stiff sheet of plain paper or (preferably) clear plastic. Sprinkle filings over the paper or plastic. Tap the paper or plastic to allow the filings to move slightly so that they line up in the field. You should obtain a pattern similar to that shown in Figure 16.7.

An alternative method of doing this uses a small compass called a **plotting compass**. When a plotting compass is placed in a magnetic field, its needle turns to indicate the direction of the field. Activity 16.1 describes how to use a plotting compass to show the pattern of a magnetic field. When drawing magnetic field patterns, the field lines should never cross and they should include arrows, pointing from magnetic north to magnetic south.

Plotting field lines

In pairs, design an experiment to plot a field pattern around a bar magnet. Create a worksheet which gives instructions on how to do the experiment. There should be at least ten field lines (including at least two from each side of the magnet). In addition to the bar magnet, the only pieces of equipment needed for the experiment are a plotting compass, a pencil and a sheet of plain paper.

In your worksheet remember to include:

- how a compass works and how it can reveal magnetic field lines
- a clear step-by-step method for plotting the field lines (including helpful sketches).

You could provide an optional extension task such as: plot the field lines between two bar magnets that are attracting or repelling. (In this case, make sure you suggest a way to prevent the magnets from moving.)

You could also produce a very short podcast (maximum two minutes) to demonstrate how to do the experiment.

After you have created your worksheet, you will have the opportunity to look at the worksheets written by other pairs. You should note any physics you have learned, and any ideas for making your own worksheet or presentation clearer or more engaging in the future.

Provide feedback on the worksheets produced by other pairs. As you give feedback on the worksheets, think about these questions:

- Is the physics of a how a compass works explained clearly?
- Could you follow the steps in the method?
- Are any steps missing or unclear?

Discuss any improvements that could be made. Each pair should note down the feedback and, if there is time, make any improvements.

Questions

5 **a** Sketch the field pattern around a bar magnet

b Someone has drawn the field pattern but forgot to label the poles. Do the arrows point towards or away from the magnetic north pole?

c When looking at a field pattern, how would you know where the magnetic field is strongest?

d Where is the field strongest on a bar magnet?

6 Figure 16.9 shows the Earth's magnetic field.

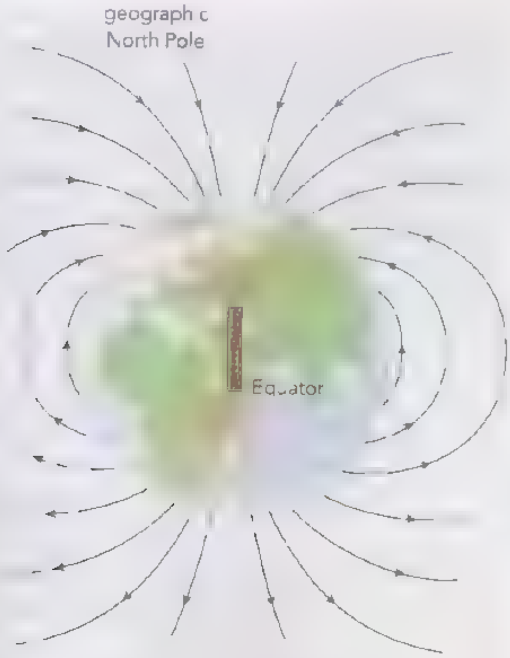


Figure 16.9: The Earth's magnetic field

c Is the magnetic field stronger at the Equator or at the geographic North Pole? Explain your answer.

d Why is a compass very difficult to use near to the north magnetic pole?

A compass needle inside a compass is a lightweight bar magnet suspended at its centre of gravity on top of a tiny vertical column.

a What will the compass needle line up with when it is suspended (held at a point) so that it can move freely?

b What magnetic pole is at the geographical North Pole when the north pole of the compass needle points in that direction?

Interacting magnetic fields

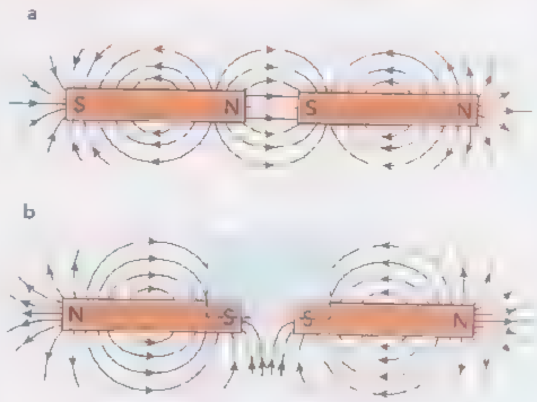


Figure 16.10a: The attraction between two opposite magnetic poles shows up in their field pattern. **b:** The field pattern for two like poles repelling each other.

We can show the field patterns for two magnets attracting (Figure 16.10a) and repelling (Figure 16.10b) each other. Notice that there is a point between the two repelling magnets where there is no magnetic field.

When two bar magnets are placed close together their magnetic fields interact (affect each other) and produce a new pattern of magnetic lines of force. From these patterns, it is possible to say whether the magnets will attract or repel.

Notice that, in Figure 16.10b, the field lines from each magnet between the south poles are in the same direction. The field lines inside the box are all pointing downwards and are close together, so the field there is stronger than the field at the north poles. The magnets will move from where the field is stronger to where it is weaker – so like poles repel. A similar argument can be used to explain why unlike poles attract. Activity 16.2 is an alternative model to explain magnetic attraction and repulsion.

An imaginary model to explain magnetic attraction and repulsion

Sometimes it helps to have an imaginary model to understand the physics which causes something to happen, for example, to understand the physics in magnetic attraction.

Imagine that magnetic field lines are like stretched elastic bands that want to pull the two ends closer together. Imagine also that there is pressure between the field lines pushing them apart and that, the closer the lines, the bigger this pressure is.

Sketch the field lines between and around:

- a pair of like poles
- a pair of unlike poles.

Use this imaginary model to explain the attraction and repulsion.

If you can visualise what is happening it should help you to remember how to sketch the patterns.

Models are an important tool in physics.

- Did Activity 16.2 help you to visualise what is going on when magnets and magnetised objects attract and repel?
- Did it help you to remember how to sketch the field patterns?
- Can you suggest a better model?

Electromagnets

Using magnetic materials is only one way of making a magnet. An alternative method is to use an **electromagnet**. A typical electromagnet is made from a coil of copper wire. A coil like this is sometimes called a **solenoid**. When a current flows through the wire, there is a magnetic field around the coil (Figure 16.11). Copper wire is often used, because of its low resistance, though other metals will do. The coil does not have to be made from a magnetic material. The point is that it is the electric current that produces the magnetic field.

electromagnet: a coil of wire that acts as a magnet when an electric current passes through it

solenoid: an electromagnet made by passing a current through a coil of wire

You can see that the magnetic field around a solenoid (Figure 16.11) is similar to that around a bar magnet (Figure 16.8). One end of the coil is a north pole, and the other end is a south pole. In Figure 16.11, the field lines emerge from the left-hand end, so this is the north pole.

There is no way to change the strength of a permanent magnet, but there are three ways to increase the strength of an electromagnet:

- Increase the current flowing through it: the greater the current, the greater the strength of the field.
- Increase the number of turns of wire on the coil: this does not mean making the coil longer but packing more turns into the same space to concentrate the field.
- Add a soft iron core: an iron core becomes strongly magnetised by the field, and this makes the whole magnetic field much stronger.

Figure 16.11: A solenoid. When a current flows through the wire, a magnetic field is produced. The field is similar in shape to that of a bar magnet. Note that the field lines go all the way through the centre of the coil.

Electromagnets have the great advantage that they can be switched on and off. Simply switch off the current and the field around the coil disappears. This is the basis of a number of applications. For example, the electromagnetic cranes that move large pieces of metal and piles of scrap around in a scrapyard (Figure 16.12). The current is switched on to start the magnet and pick up the scrap metal. When it has been moved to the correct position, the electromagnet is switched off and the metal is released.

Electromagnets are also used in electric doorbells, loudspeakers, electric motors, relays and transformers. These uses are described in detail later in Chapters 20 and 21.

Figure 16.12: Using an electromagnet in a scrapyard. With the current switched on, a steel object or pile of scrap can be lifted and moved. Then the current is switched off to release it.

Questions

7 a Name three ways to increase the strength of an electromagnet.

b What are the advantages of an electromagnet over a bar magnet.

c What does an electromagnet need that a permanent magnet does not?

How does the strength of an electromagnet depend on the number of turns?

Arun investigated how the strength of an electromagnet varies with the number of turns. Figure 16.13 shows the equipment he put together, and Table 16.3 shows the data he collected.

Arun made sure that the pole at the bottom of the electromagnet was the same as the top of the permanent magnet so that they would repel.

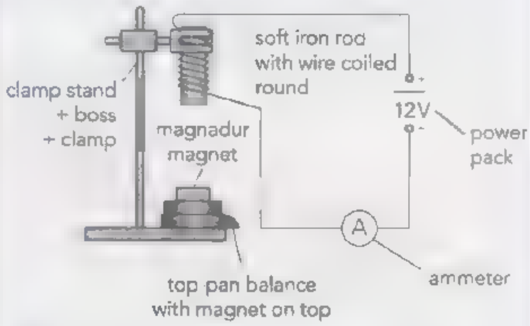


Figure 16.13: Apparatus for investigating the strength of an electromagnet.

Number of turns	Mass / g
6	0.21
8	0.29
10	0.34
12	0.38
14	0.43
16	0.47
18	0.54
20	0.59

Table 16.3: Experimental data

CONTINUED

1 Plot a graph of mass against the number of turns.

2 The mass of the permanent magnet is not changing, so what is causing the apparent change in mass?

3 What does the graph tell Arun about the strength of the electromagnet as the number of turns increases?

4 Why is it important that the electromagnet and permanent magnet are repelling (and not attracting)? How could Arun have checked this before collecting data?

5 How else could Arun increase the strength of the electromagnet?

The field around a solenoid

When an electric current flows through a solenoid, a magnetic field is produced both inside and outside the coil (see Figure 16.11). The magnetic field inside an electromagnet is uniform. This means that the field lines are parallel and the same distance apart. The field around the outside of a solenoid is similar to that around a bar magnet:

- One end of the solenoid is the north pole and the other end is the south pole. Field lines emerge from the north pole and go in to the south pole.
- The field lines are closest together at the poles, showing that this is where the magnetic field is strongest.
- The lines spread out from the poles, showing that the field is weaker in these regions.

The strength of the field can be increased by increasing the current. The field can be reversed by reversing the direction of the current

Question

8 a Sketch a diagram of the magnetic field pattern around a solenoid

b How would the pattern change when the current through the solenoid is reversed?

EXPERIMENTAL SKILLS 16.[illegible]

Which magnetic pole sits below the geographical North Pole?

The red end of a compass needle points towards the North Pole of the Earth. If you look on the Internet, it is not clear whether the magnetic pole near the geographical North Pole is magnetic north or magnetic south. Therefore, you need to work out whether the red end of a compass needle is a north or south magnetic pole.

You need to ensure you know which way **conventional current** is flowing (from the positive to the negative of a battery or power pack).

You will need:

- electromagnet
- compass.

Method

1 Look along the electromagnet from either end.

If conventional current is flowing clockwise around the end loop, you are looking at the south pole like the arrows on the S (as shown in Figure 16.14a).

If conventional current is running anticlockwise, like the arrows on the N (Figure 16.14b), you are looking at the north pole.

The magnetic poles in Figure 16.11 are drawn correctly. Imagine standing at the left-hand end of the electromagnet looking along it, as if you were looking down a long tunnel. Conventional current would be flowing anticlockwise, telling you that you were at the north pole.

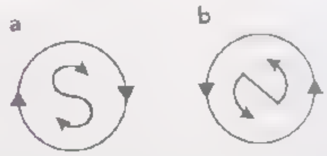


Figure 16.14

CONTINUED

2 Bring your compass towards either pole of the electromagnet. Use your observations to decide whether the red end of your compass needle is north or south. Use this information to decide which magnetic pole sits below the geographical North Pole.

[illegible]

conventional current: the direction positive charges would flow in a complete circuit, from the positive to negative terminals of a cell, and opposite to the direction that electrons flow

PROJECT

Read this newspaper extract.

COMPASS CONFUSION: HIKER ALMOST KILLED BY HIS COMPASS

An experienced hiker from the USA who became lost in the Australian Outback was rescued by the police last week. He complained, 'my compass stopped working'. A spokesman for the Western Australia Police Force was quoted as saying, 'this gentleman is lucky to be alive. The hiker was using a compass designed for use in the USA and had not realised until it was too late that he needed to buy a compass here in Australia.'

[illegible]u are a science journalist whose job it is to explain [illegible] science behind this story. You can decide [illegible]er you write an article, write a script for a [illegible]sion news item or produce a podcast.

[illegible]ber that your audience are not scientists [illegible]mes explaining a problem needs ideas from [illegible]more topics, as is the case here. You will need [illegible] why magnetic compasses stop working [illegible]ed in the opposite hemisphere (for example, [illegible]ss designed for the northern hemisphere [illegible] in the southern hemisphere). You need [illegible]rams or video clips to help your audience [illegible] explanation.

[illegible] a compass, you should hold it flat (that [illegible] the ground). The compass needle [illegible]ed the card) should be parallel to [illegible] of the compass (when viewed from the side) and needs to be able to swing clockwise or anticlockwise when viewed from above. However, you should recall that a compass needle lines up with the magnetic field lines, which are not parallel to the ground in Australia.

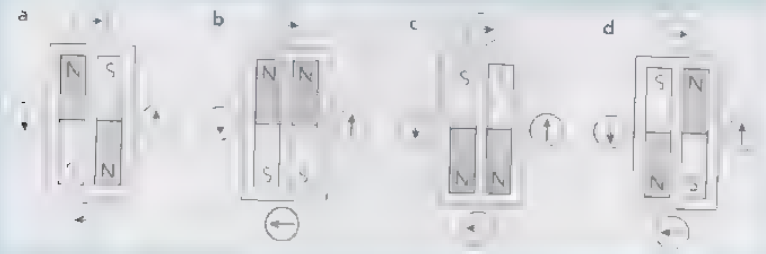
You will need to explain why the magnetic field lines are not parallel to the ground in Australia. You need to sketch what the compass needle looks like when viewed from the side. It looks like a tiny see-saw balanced on a tiny pillar at its mid-point (look back at Chapter 4 if necessary). Use the principle of moments and the idea of equilibrium to explain how a compass needle is made to be parallel to the base plate (and the ground). Then explain why this is a particular problem when a compass designed for one hemisphere is taken and used in the other.

Magnets have a north pole and a south pole.
Magnetic field lines are drawn with an arrow from north to south, which is the direction of the magnetic force
Like poles repel and unlike poles attract.
Magnetic elements include iron, cobalt and nickel. Metal alloys (for example steel) containing these elements are also magnetic.
Magnetic materials can be magnetised while non-magnetic materials (like rubber and glass) cannot be magnetised
A permanent magnet can attract unmagnetised magnetic materials by inducing magnetism in them
A hard magnetic material like steel is difficult to magnetise and demagnetise.
A soft magnetic material like soft iron is easy to magnetise and demagnetise.
A magnetic field is a region of space around a magnet or electric current in which a magnet will feel a force
A magnetic field pattern around a (bar) magnet can be produced using a plotting compass.
A magnetic field line is the line (direction) of force on the north pole of the magnet, which is why a magnet (for example, a compass needle) lines up with it.
An electromagnet (or solenoid) is a magnet created when a current is passed through wire, which is usually shaped into a coil.
The strength of an electromagnet increases with the number of turns in the coil, the strength of the current and if it has a soft iron core.
The advantages of an electromagnet over a permanent magnet are that its strength can be changed, it can be switched on and off and it can be reversed
The magnetic forces of attraction and repulsion between magnets are caused when their magnetic fields interact (affect each other) and produce a new pattern of magnetic lines of force.
The closer together magnetic field lines are to each other, the stronger the magnetic field

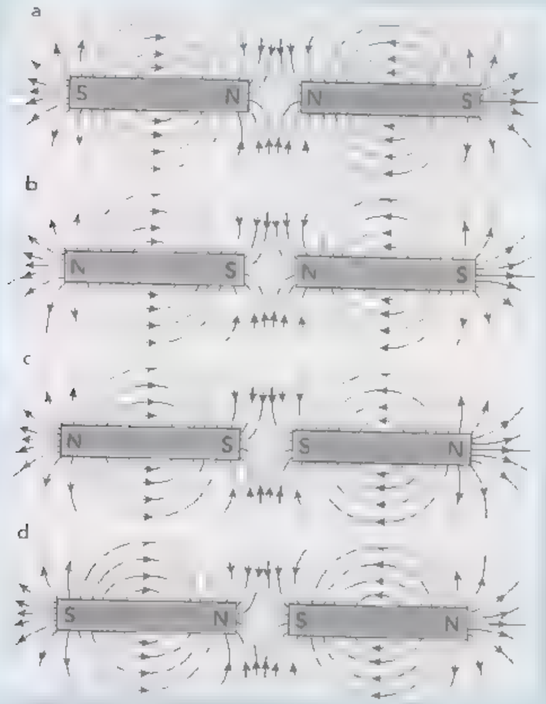
1 Some metals and alloys are magnetic. Which of these is magnetic? [1]

A aluminium
B copper
C gold
D steel

2 Which arrangement of bar magnets leads to the field pattern revealed by the plotting compasses? **[1]**



3 Which of these magnetic field patterns is correct? **[1]**



4 a Copy this image of a bar magnet and draw the field lines you would expect to see around it. **[2]**

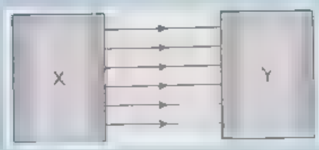
b **Explain** how you could use a plotting compass to investigate the magnetic field around a bar magnet. You may draw a diagram to help your answer. **[3]**

[Total: 5]

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

CONTINUED

5 The diagram shows the magnetic field between magnetic poles X and Y.

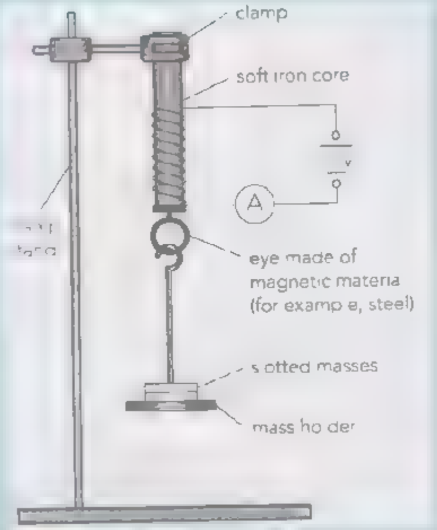


a Which pole is at X? [1]

b If the magnets are released, in which direction will they move? [1]

[Total: 2]

6 Karamveer investigated how the strength of an electromagnet varied with current. He used an arrangement like the one in the diagram. He passed a current through an electromagnet so that it attracted a small steel plate. For each current he passed through the coil, he suspended more masses from the bottom of the steel plate until the steel was pulled away from the electromagnet.



Current / A	Force / N
0	0.00
2	0.60
4	1.20
6	1.90
8	2.40
10	3.00

a Plot a graph of force against current. [3]

b State how the strength of the electromagnet varies with the current passing through the coil. [1]

c State **two** other ways that the strength of an electromagnet can be increased. [2]

d An electromagnet can be switched on and off. Suggest one situation where this would be an advantage over the constant field of a permanent magnet. [1]

e In terms of forces, state why the steel plate falls from the electromagnet once the suspended masses exceed a certain value. [1]

[Total: 8]

state: express in clear terms

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations

7 a What is the difference between a magnetically soft and a magnetically hard material? [1]

b Give an example of a magnetically hard material and suggest where it might be used. [1]

c Give an example of a magnetically soft material and suggest where it might be used. [1]

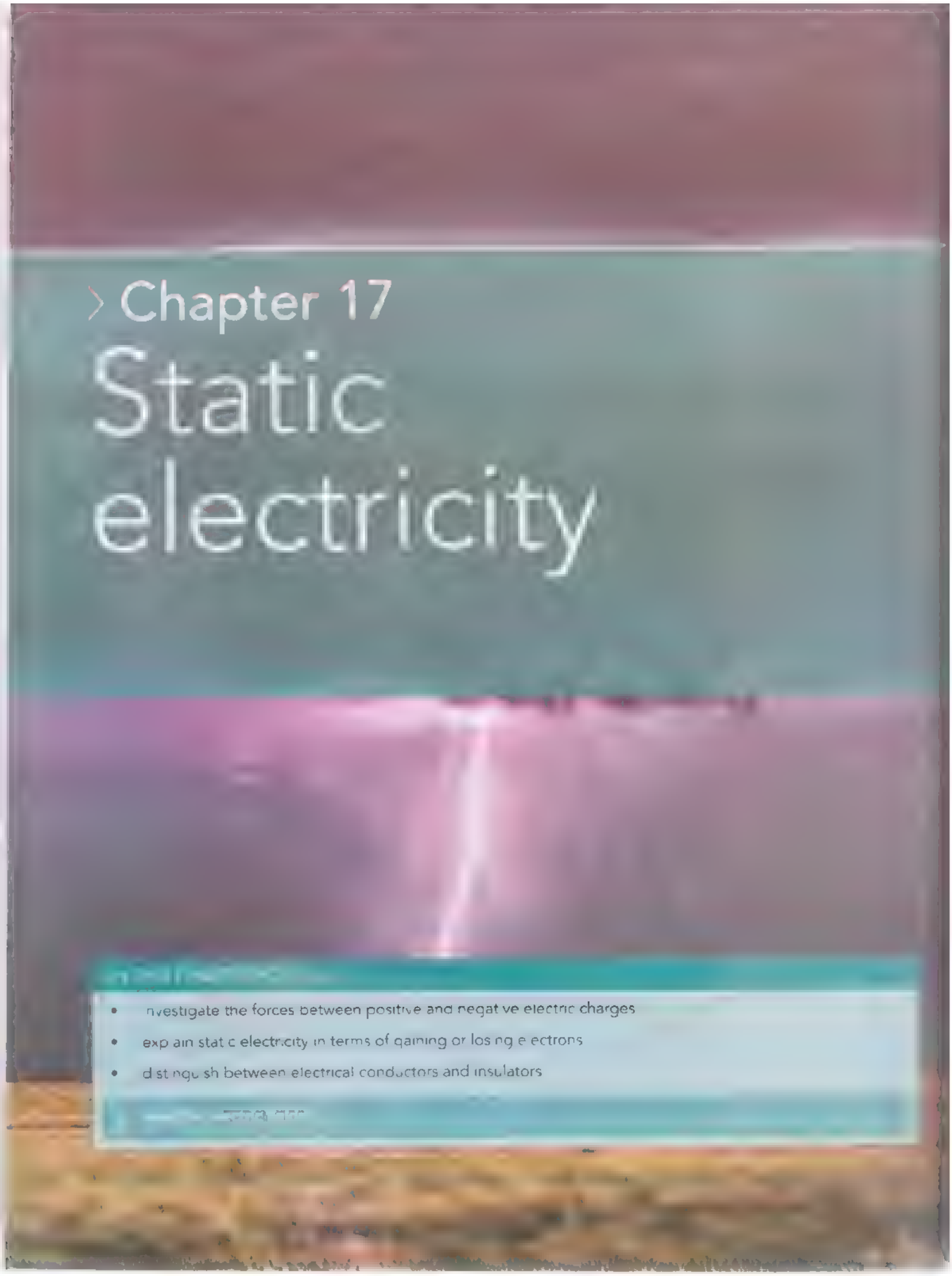
[Total: 3]

give: produce an answer from a given source or recall/memory

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible] Topic...	Needs more work	Almost there	Confident to move on
Recall the names of the two poles of a magnet.	16.1			
Recall the direction that the arrows on a field line should point.	16.2			
Recall what happens between like poles and unlike poles.	16.2			
Identify common magnetic materials	16.1			
Recall the difference between magnetic and non-magnetic materials.	16.1			
Account for induced magnetism	16.2			
Recall examples of hard and soft magnetic materials and the difference between them	16.1			
Draw the pattern of magnetic field lines around a bar magnet and describe an experiment to plot them, including the direction arrows.	16.2			
Recall why a compass needle or other permanent magnet lines up with the field lines when it is placed in a magnetic field.	16.2			
[illegible]ribe electromagnets (and solenoids).	16.2			
[illegible]scribe the three ways in which the strength of an electromagnet can be changed.	16.2			
Describe the advantages of an electromagnet over a permanent magnet.	16.2			
[illegible]n that magnetic forces are due to interactions [illegible]en magnetic fields.	16.2			
[illegible]e spacing of the field lines to work out the [illegible] strength of the magnetic field.	16.2			



Chapter 17
Static electricity

- investigate the forces between positive and negative electric charges
- explain static electricity in terms of gaining or losing electrons
- distinguish between electrical conductors and insulators

In a small group, discuss what you know about electricity. Organise your ideas into a mind map. Include as many of the following words as possible, giving definitions and examples wherever you can: electron, charge, current, static, shock, voltage, conductor, insulator.

One member of the group should now stay with the map to explain it to other groups. The rest of the group should visit the maps of different groups. Having done this, return to your own group and add any additional information to your map.

Figure 17.1a: Lightning and electrical sparks are both caused by a large build-up of electric charge. **b:** electrical hazard symbol

The similarity between lightning bolts and the sign used for electrical hazards is not a coincidence. A large build-up of electrical charge can cause the air to break down and conduct electricity, potentially delivering a fatal electric shock. In December 2014, a potential difference of 1.3 billion volts was recorded during a thunderstorm over Ooty in Southern India.

The US scientist Benjamin Franklin was lucky to survive his experiments into this kind of electricity. He suspected lightning was a form of electricity due to the similarity between a lightning flash and the sparks he produced in his laboratory. To investigate he flew a kite into a thundercloud. To avoid being electrocuted, he included a metal key at the bottom of the kite string, and attached a length of ribbon to the key. Holding the ribbon, he was relatively safe from electrocution (although other people were killed when they repeated his experiment). As a bolt of lightning struck the kite, Franklin saw the fibres of the kite string stand on end and a spark jumped from the key to the ground.

Franklin's method was hazardous, and by flying a kite into the cloud, he may have brought on a lightning flash and thereby affected the situation he was investigating. Sunil Gupta and the team who measured the potential difference in the Ooty storm used a rather different method. They studied muons – a type of subatomic particle – as they passed through the storm cloud. The muons gained energy from the potential difference in the cloud, increasing the number which reached the scientists' muon sensors. This allowed the team to calculate the potential difference within the cloud

Discussion questions

1 Franklin made important discoveries about static electricity, but his experiment would be considered too dangerous to be carried out now. Should scientists be allowed to conduct hazardous investigations?

2 Gupta's observations did not affect the situation he was studying. Why this is an important feature of scientific research?

17.1 Charging and discharging

We experience static electricity in a number of ways in everyday life, including lightning flashes. You may have noticed tiny sparks when you take off clothes made of synthetic fibres. You may have felt a small shock when getting out of a car. An electrostatic charge builds up on the car and then discharges through you when you touch the metal door. You may have rubbed a balloon on your clothes or hair and seen how it will stick to a wall or ceiling.

When you rub a plastic object (for example, a balloon) with a cloth, both are likely to become electrically charged. You can tell that this is so by holding the balloon or the cloth close to your hair – they attract the hair.

Figure 17.2: Objects which have electrostatic charge can attract light objects such as hair or paper

You have observed that static electricity is generated by friction. You have also observed that a charged object may attract uncharged objects.

Now we have to think systematically about how to investigate this phenomenon. First, how do two charged objects affect one another? Figure 17.3 shows one way of investigating this. A plastic rod is rubbed with a cloth so that both become charged. The rod is hung in a cradle so that it is free to move. When the cloth is brought close to it, the rod moves towards the cloth (Figure 17.3a). When a second rod is rubbed in the same way and brought close to the first one, the hanging rod moves away (Figure 17.3b). Now we have seen both attraction and repulsion. This suggests that there are two types of static electricity. Both rods have been treated in the same way, so we expect them to have the same type of electricity. The cloth and the rod must have different types.

The two types of static electricity are referred to as positive charge and negative charge. We can explain the experiments shown in Figure 17.3 by saying that the process of rubbing gives the rods one type of electric charge (say, negative), while the cloth is given the opposite type (say, positive). Figures 17.3c and 17.3d show the two experiments with the charges marked.

static electricity: electric charge held by a charged insulator

electrostatic charge: a property of an object that causes it to attract or repel other objects with charge

positive charge: the type of electric charge carried in the nucleus of an atom

negative charge: the type of electric charge carried by electrons

From these experiments, we can also say something about the forces that electric charges exert on each other:

- Two positive charges will repel each other.
- Two negative charges will repel each other.
- A positive charge and a negative charge attract each other.

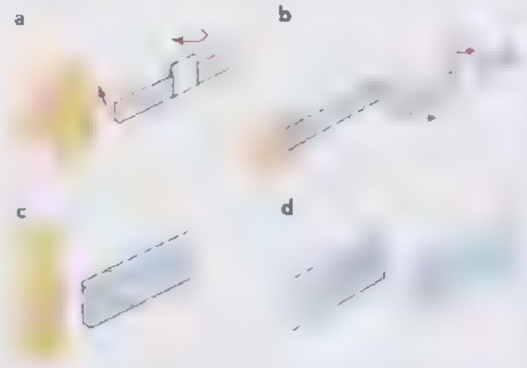


Figure 17.3: Two experiments to show the existence of two, opposite, types of static electricity. **a:** The charged rod and cloth attract one another **b:** The two charged rods repel one another. **c:** The rod and the cloth have opposite electric charges. **d:** The two rods have the same type of electric charge

You can see that this rule is similar to the rule we saw for magnetic poles in Chapter 16 But do not confuse magnetism with static electricity! Magnetism arises from magnetic poles static electricity arises from electric charges. When you rub a plastic rod, you are not making it magnetic.

Questions

1 Copy and complete these sentences.

There are two types of charge called ______ and ______.

Two objects with the same charge will ______ and two objects with opposite charges will ______.

2 Figure 17.4 shows a child's hair standing on end after the child has been on a trampoline

Figure 17.4

a How does bouncing on the trampoline cause the child's hair to become charged?

b The individual hairs are repelling each other. What does this tell you?

3 Explain why, after walking on a nylon carpet, you may get a small shock when you touch a metal door handle

EXPERIMENTAL SKILLS 17.1

Investigating static electricity

In this experiment you will find out about static electricity by charging materials and observing how they behave.

You will need:

- polythene and acetate or glass rods
- cloths of different materials
- paper stirrups with fine thread
- clamp and stand
- watch glass
- balloons
- tiny pieces of thin paper.

Getting started

Investigate how much you need to rub the rods in order to charge them. Test this by using the rod to pick up little pieces of paper.

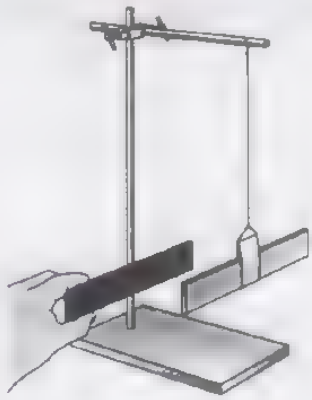


Figure 17.5: Set-up for investigation.

Method

1 You need to be sure that you can place the rods so that they can turn freely, either by hanging them in the paper stirrup, or by placing them on an upturned watch glass. Try this out with your rods.

CONTINUED

2 Rub a polythene rod with a woollen cloth, making sure that you rub the full length of the rod. Hang the rod or place it on a watch glass

3 Rub another polythene rod and bring one end close to an end of the first rod. Do they attract or repel?

4 Rub an acetate or glass rod and repeat the test. What do you observe?

5 Try different combinations of rods. Try a cloth of a different fabric. Given that a polythene rod, rubbed with a woollen cloth, gains a negative charge, what can you say about the charges gained by the cloth and by the other rods?

6 Blow up a balloon and rub it. Can you determine whether it gains positive or negative charge? (Hint: polythene becomes negative and acetate becomes positive.)

Questions

1 Some students investigate polythene and acetate rods. They find that the two rods attract each other. One student says this proves that the rods have opposite charge. Explain why the student is wrong.

2 Describe what the students would need to do in order to prove that the rods have opposite charges.

17.2 Explaining static electricity

The Ancient Greeks knew something about static electricity. Amber is a form of resin from trees, which hardens and becomes fossilised. It looks like clear, orange plastic. The Greeks knew that, when rubbed, amber could attract small pieces of cloth or hair.

Like the Ancient Greeks, Franklin had no idea about electrons – these particles were not discovered until 100 years later. However, that did not stop Franklin from developing a good understanding of static electricity.

In the discussion that follows, we will talk about electrons. They make it much easier to understand what is going on in all aspects of electricity.

Figure 17.6: An insect trapped in resin as it hardened. Resin is a good insulator and easily becomes electrostatically charged.

Friction and charging

It is the force of friction that causes charging. When a plastic rod is rubbed on a cloth, friction transfers tiny particles called electrons from one material to the other. When the rod is made of polythene, usually electrons are transferred from the cloth to the rod.

Electrons are a part of every atom. They are negatively charged, and they are found on the outside of the atom. The nucleus in the centre of the atom has a positive charge. The positive and negative charges in an atom are equal so overall an atom has no electric charge – we say that it is **neutral**. Since the outer electrons are relatively weakly held in the atom, they can be pulled away by the force of friction. When an atom has lost an electron, it becomes positively charged.

neutral having no overall positive or negative charge

Charging is always the result of gaining or losing electrons. Positive charge is not transferred.

- An object which gains electrons becomes negative.
- An object which loses electrons becomes positive.

Since a polythene rod becomes negatively charged when it is rubbed with a cloth, we can imagine electrons being transferred from the cloth to the rod (see Figure 17.8). It is difficult to explain why one material pulls electrons from another. The atoms that make up polythene contain positive charges, and these must attract electrons more strongly than those of the cloth.

Remember that it takes two different materials to generate static electricity. One material becomes positive, the other negative.

Conductors and insulators

You may have noticed that all the examples of objects becoming charged involve non-metals. Metals are electrical conductors, which means electrons can move through them and the metal doesn't stay charged. Gold and copper are particularly good electrical conductors. Non-metals, such as glass, plastic and amber are electrical insulators.

So why can charge move through conductors but not through insulators? In insulators, the electrons are tightly bound to their atoms and not easily removed. In conductors some of the electrons are free to move between atoms (these electrons are sometimes referred to as free electrons).

When you rub a polythene rod, it gains electrons from the cloth and so becomes negatively charged. The electrons cannot move through the polythene, so the end which was rubbed remains charged.

When a copper rod is rubbed, electrons are also transferred by friction, but these electrons are free to move, so they flow through the rod, through your hand and into the Earth. This means the copper rod does not become charged.

A metal object can be charged if it is held by an insulating handle. In this case the charge will spread evenly through the conductor.

electrical conductor: a substance that allows the flow of electrons (electric current)

electrical insulator: a substance that inhibits the flow of electrons (electric current)

EXPERIMENTAL SKILLS 17.1

Investigating conductors and insulators

In this experiment you will find test materials to find out which are conductors and which are insulators.

You will need:

- cell
- lamp
- wires with crocodile clips
- materials to test

Figure 17.7: Circuit for testing materials.

Getting started

Connect the cell and lamp in a simple circuit to make the lamp light.

Make a gap in the circuit by removing a wire. Explain why the lamp no longer lights and consider how placing materials in the gap will help you decide if they are conductors or insulators.

Method

1. Connect the circuit as shown in Figure 17.7.
2. Using the crocodile clips, attach a material into the gap in the circuit.
3. Observe whether the lamp lights. If it does, it is a conductor, if not it is an insulator.
4. Record your results in a table.

Question

1. The wires you used are made of copper covered in plastic. Explain why these materials were chosen.

Figure 17.8: When a polythene rod is rubbed with a cloth, electrons are transferred from the cloth to the polythene. The rod now has an overall negative charge and the cloth has an overall negative charge.

Questions

4 Copy and complete these sentences.

When a polythene rod is rubbed, ______ move from the ______ to the ______.

This means the rod becomes ______ and the cloth becomes ______.

5 a Draw a diagram similar to Figure 17.8 to show how an acetate rod becomes positively charged by losing electrons.

b Write sentences similar to those you completed in question 17.4 to explain how the acetate becomes charged.

6 When you hold a polythene rod and rub it with a cloth, it becomes charged. If the rod is made of metal, it will not become charged. Explain this difference by describing what happens to the electrons in each case.

Take two minutes to summarise what you have learnt so far in this chapter on one sheet of paper.

Now, take two more minutes to condense your notes. You may use ten words and four diagrams.

Compare summaries with a partner. Assume that you can use only four words and one diagram as a reminder in a test. Which diagram and four words would you choose?

Which part of Activity 17.1 did you find most useful? Summarising, condensing or sharing? Consider how this might help you when revising for a test.

17.3 Electric fields

Figure 17.9: The comb has been charged by rubbing it. It attracts the water when it is held close to the water.

A charged object can affect other objects, both charged and uncharged, without actually touching them. For example, a charged plastic rod can exert a force on another charged rod placed close by.

We say that there is an **electric field** around a charged object. Any charged object placed in the field will experience a force on it.

electric field: a region of space in which an electric charge will experience a force

There are similarities between electric fields and magnetic fields, but take care not to confuse electric fields with magnetic fields. A magnet does not attract electric charges. A charged object does not attract a magnet.

Representing an electric field

A charged object is surrounded by an electric field. If a charged object moves into the electric field of a charged object, it will experience a force – it will be attracted or repelled. Figure 17.10 shows how we represent an electric field by lines of force (or electric field lines). This is similar to the way we represent a magnetic field by magnetic field lines.

The lines of force are shown coming out of a positive charge and going in to a negative charge. This is because the lines indicate the direction of the force on a positive charge placed in the field. A positive charge is repelled by another positive charge and attracted by a negative charge.

Figure 17.10c shows the field between two oppositely charged parallel plates. The lines of force between the plates are straight and parallel to one another (except at the edges).

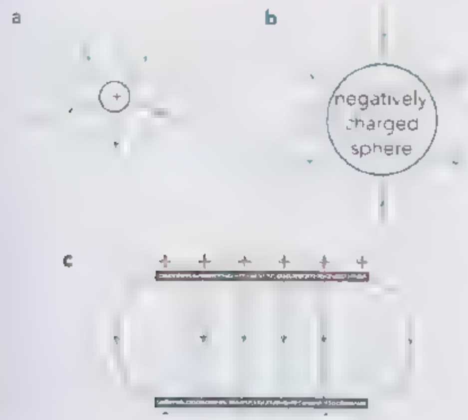


Figure 17.10: The electric field around a charged object is represented by lines of force. a: An isolated positive charge b: A negatively charged sphere c: Two parallel plates with opposite charges.

Question

1 Draw the magnetic field around:

a an isolated negative charge

b two vertical metal plates – one positive and the other negative.

What is electric charge?

In physics, we find it relatively easy to answer questions such as 'What is a rainbow?' or 'How does an aircraft fly?' It is much harder to answer an apparently simple question like 'What is electric charge?'. As with energy, we have to answer it by explaining how objects behave when they have it (energy or charge).

Objects with the same sign of charge repel one another. Objects with opposite charges attract. This is not a very satisfying answer, because magnetic poles behave in the same way: north poles repel north poles and attract south poles. Because electric charge is a fundamental property of matter, we have to get a feel for it, rather than having a clear definition.

The electric force between two charged objects is one of the fundamental forces of nature. (The force of gravity between two masses is another fundamental force.) The electric force holds together the particles that make up an atom. It holds atoms together to make molecules, and it holds molecules together to make solid objects. Just think: whenever you stand on the floor, it is the electric force between molecules that prevents you from falling through the floor. It is a very important force.

Charged particles

We have already seen that electrons are the charged particles that are transferred from one object to another when they are rubbed together. Electric charge is a property of the particles that make up atoms.

Charge is measured in **coulombs (C)**, named after Charles-Augustin de Coulomb, a French physicist. He discovered that the force between two charged objects depends on how big their charges are and on how far apart they are.

An electron is a negatively charged particle. It is much smaller than an atom, and only weakly attached to the outside of the atom. It is held there by the attraction of the positively charged nucleus of the atom. The nucleus is positively charged because it contains positively charged particles called **protons**.

An electron has a very tiny amount of electric charge. The **electron charge** is so small that it takes more than 6 million million million electrons to make 1 C of charge.

electron charge = −0.000 000 000 000 000 000 16 C
or -1.6×10^{-19} C

A proton has exactly the same size of charge as an electron, but positive, so the **proton charge** is:

proton charge = +0.000 000 000 000 000 000 16 C
or $+1.6 \times 10^{-19}$ C

No-one knows why these values are exactly the same size (or even if they are exactly the same size), but it is fortunate that they are because it means that an atom that contains, say, six protons and six electrons is electrically neutral. If all the objects around us were made of charged atoms, we would live in a shocking world!

Question

8 Calculate the number of electrons needed to give a charge of one coulomb.

coulomb (C): the SI unit for electric charge

proton: a positively charged particle found in the atomic nucleus

electron charge: the electric charge of a single electron = -1.6×10^{-19} C

proton charge: the electric charge of a single proton = $+1.6 \times 10^{-19}$ C

Figure 17.11: A carpet in a shop can cause a shock.

Walking across a carpet can cause friction, which leads to people becoming electrostatically charged. Touching another person, or a conducting object such as a metal stair bannister, can cause a shock as the charge flows through to earth, discharging the person. These shocks are not usually dangerous but can be uncomfortable.

A manager of a large store has received a lot of complaints from customers who are experiencing painful shocks as they shop. The manager thinks it may be due to the carpet on the shop floor which is made of a hard-wearing material called polypropylene. The store manager wants to investigate whether she should invest in a new carpet that is less likely to create static. Until she does this, she wants to be able to advise customers on how to avoid shocks.

Your tasks as her scientific consultant are:

1 Explain what is happening. As an interim measure, she would like leaflets to give to shoppers to help them understand what is happening and what they can do to minimise shocks. Could customers discharge regularly before too much charge builds up? Or would it help if they picked up their feet rather than shuffling?

2 Design the leaflet. It must have no more than 50 words and it should be illustrated.

3 Consider how new carpets could be tested to find out which create the most static. Testing by shocking people is not easy or ethical. Instead you should look at charging the carpets by friction and investigating the force of attraction or repulsion they produce. You will need to give step-by-step instructions for a fair test investigation.

Exchange leaflets and investigation plans with another student. Give them written feedback by answering the following points:

- Does the leaflet make it clear how charging happens?
- Does the leaflet give clear advice on avoiding shocks?
- Will the investigation provide valid data?
- Does the plan control all variables in order to give a fair test?

SUMMARY

There are two types of charge: positive and negative.
Like charges repel, opposite charges attract.
Conductors allow charge to flow. Insulators do not allow charge to flow.
Insulators can be charged by friction, which causes the loss or gain of electrons.
An electric field is the area around a charged object in which a charge will experience a force
Electric fields can be represented by field lines which show the direction of the force on a positive charge
Insulators are materials in which electrons are fixed in place. Conductors have free electrons.

[illegible]

1 Which of these describes how an object becomes positively charged? **[1]**

A It gains positive charge

B It loses positive charge

C It gains negative charge

D It loses negative charge

[illegible] When an object is charged by friction, which particle is transferred? **[1]**

A [illegible]ton

B [illegible]ectron

C [illegible]eutron

D [illegible]m

[illegible]tively charged rod is suspended so it can move freely. A negatively [illegible] rod is brought close to it. What will happen to the positive rod? **[1]**

[illegible] repel.

[illegible]thing will happen

[illegible]t possible to predict what will happen from the information given

[illegible] attract

5 A student investigates charging polythene by friction. She takes two identical strips and rubs each with a cloth. She holds the two strips together and they move apart

a Explain why the strips move apart [2]

The student repeats the experiment using two strips of aluminium.

b **State** and **explain** what the student would see with the aluminium strips. [2]

c A plastic rod is charged by rubbing it with a cloth.

Which statement described what has happened to the cloth?

A The cloth becomes negatively charged because electrons transfer from the cloth to the rod

B The cloth becomes positively charged because electrons transfer from the cloth to the rod

C The cloth becomes negatively charged because protons transfer from the rod to the cloth

D The cloth becomes positively charged because protons transfer from the rod to the cloth.

6 A student combs his hair with a plastic comb. The comb becomes negatively charged.

a Explain how this happens. [2]

b Name the particles which are transferred. [1]

c The student notices his hair is now standing on end. Explain why this happens to his hair. [2]

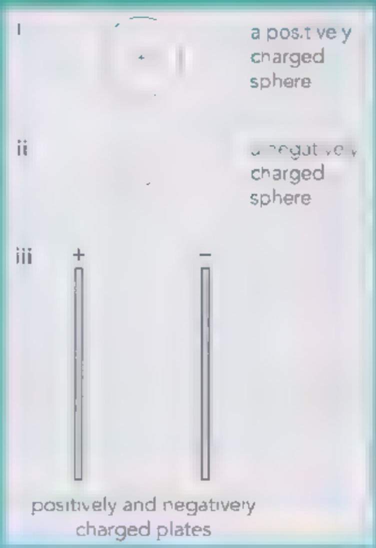
[Total: 5]

state: express in clear terms

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

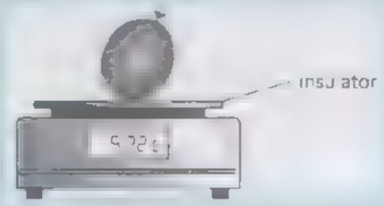
7 a Define the [illegible] electric field. [1]

b [illegible]



[Total: 7]

8 A student rubs a balloon so that it becomes positively charged. He places the balloon on top of an insulating sheet on an electronic balance.



a Explain, in terms of movement of electrons, how the balloon becomes positively charged. [2]

b The student now brings a charged plastic rod close to the balloon. The reading on the balance increases to 11.63 g. State and explain what this tells you about the plastic rod [2]

c The student repeats the experiment, but this time he places the balloon directly on to the metal pan of the balance. This time when he brings the charged rod close to the balloon, the reading on the scale decreases to 6.94 g. Explain why [3]

[Total: 7]

define: give precise meaning

9 A painter is spray painting a metal fence. The nozzle of the sprayer is negatively charged.

  a State and explain what happens to the paint droplets as they pass through the nozzle. [2]

  b Explain two ways in which this makes the spray painting more efficient. [2]

  c What charge should be given to the fence to make the process even more efficient? [1]

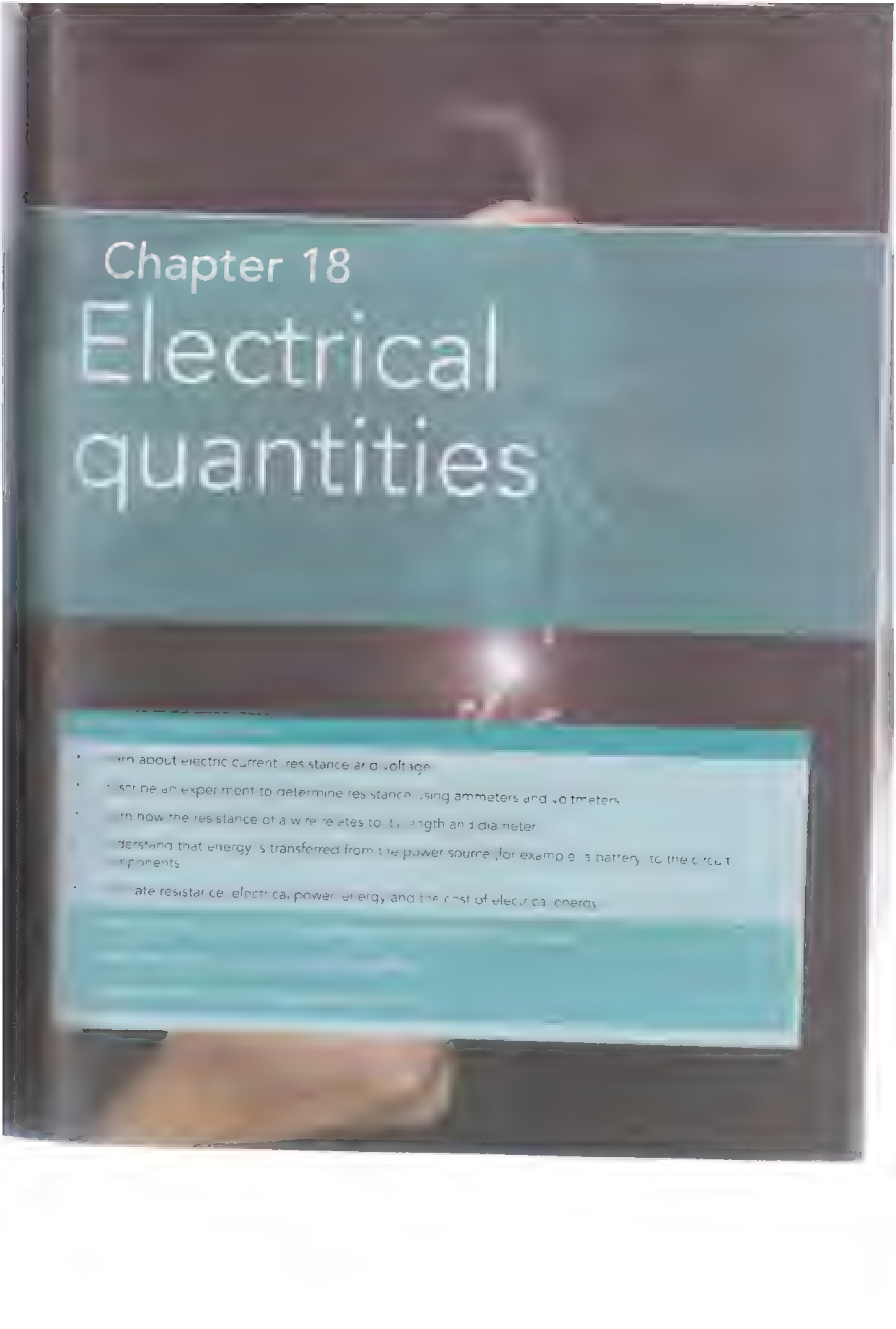
[Total: 7]

[illegible] state the points of a topic; give characteristics and main features

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	Almost there	Confident to move on
Name the two types of charge.	17.1			
Say how objects with identical or opposite charges affect each other.	17.1			
Describe experiments to show how charges can be produced and detected.	17.2			
Explain how charging by friction happens by describing what happens to the electrons.	17.2			
Define and give examples of conductors and insulators.	17.2			
Name the unit of electrical charge.	17.3			
Define what is meant by an electric field.	17.3			
Draw the field between two charged plates or around a point charge of a charged sphere, using arrows to show the direction of the field.	17.3			
Describe the difference between conductors and insulators in terms of a simple electron model.	17.3			



Chapter 18

Electrical quantities

- ...rn about electric current, resistance and voltage
- ...scribe an experiment to determine resistance using ammeters and voltmeters
- ...rn how the resistance of a wire relates to its length and diameter
- ...derstand that energy is transferred from the power source (for example, a battery) to the circuit ...ponents
- ...ate resistance, electrical power, energy and the cost of electrical energy

Does anything get used up going around a circuit?

What do batteries and cells have that gets used up?

Why can birds stand on power lines without being electrocuted?

Do you know what happens when we charge a mobile (cell) phone?

INSPIRED BY AN EEL? USING PHYSICS FOR LAW ENFORCEMENT

Jean Richer, a French astronomer, met an electric eel (Figure 18.1) during an expedition to the Amazon basin in 1671. He described it as being 'as fat as a leg' and it made his arm go numb for 15 minutes after he touched it with his finger. About 80% of an electric eel is basically a battery, with a positive terminal at its head and a negative terminal at its tail. The charge is carried by positive ions instead of electrons. It has about 5000 to 6000 stacked plates (called electroplaques). Each pair of plates is like an electric cell that can produce a voltage of about 0.15 V so that an eel can deliver a shock of 900 V and a current of up to 1 A. To save energy it can send out low voltage pulses (75 V). This makes the muscles of potential prey twitch, which can be detected by the eel. If it detects prey, the eel can send out bigger shocks when it wants to stun its victim. Some eels were taken back to be studied in Europe where they inspired the work of Italian scientists. Luigi Galvini used frogs to show that electricity made their legs move. Alessandro Volta invented the first battery based on the electric eel.

Figure 18.1: An electric eel

NASA researcher Jack Cover finished developing the TASER in 1974. He named it after the book *Tom Swift and His Electric Rifle*. TASERs are used by law enforcement officers to subdue suspected criminals without using lethal force (Figure 18.2). The TASER fires two thin insulated copper wires at the target. Once the barbs at the end of the wires hook into the skin, the person becomes part of the circuit. When a current is passed through the circuit, the person loses control of their muscles, like the victims of the electric eel.

Figure 18.2: Even without the cartridge that sends the copper wires to its target, a TASER still passes an electrical charge

Discussion questions

1. Describe how an electric eel is like a battery.
2. A TASER is like an electric eel but why does the eel not need the wires used in a TASER?

18.1 Current in electric circuits

We use electric circuits to transfer energy from a battery or power supply to components in the circuit, which then transfer the energy to their surroundings. For an electric **current** to flow, two things are needed: a complete circuit for it to flow around, and something to 'push' it around the circuit. The push might be provided by a **cell**, battery or power supply. A **battery** is simply two or more cells connected end-to-end. In most familiar circuits, metals such as copper or steel provide the circuit for the current to flow around.

Figure 18.3a shows how a simple circuit can be set up in the laboratory. Once the switch is closed, there is a continuous metal path for the current to flow along. Current flows from the positive terminal of the battery (or cell). In the circuit symbol for a cell, the longer line represents the positive terminal (see Figure 18.3b). Current flows through the switch and the filament lamp, back to the negative terminal of the battery. A current that flows in the same direction all the time is called **direct current (d.c.)**. You will meet **alternating current (a.c.)** in Chapter 21 when you learn about transformers. Alternating current is when current reverses direction. In many countries, mains electricity has a frequency of 50 Hz so it changes direction 100 times per second.

current: the rate at which electric charge passes a point in a circuit

cell: a device that provides an electromotive force (e.m.f.) in a circuit by means of a chemical reaction

battery: two or more electrical cells connected together in series

direct current (d.c.): electric current that flows in the same direction all the time

alternating current (a.c.): electric current that (periodically) changes direction

Figure 18.3b shows the same circuit as represented by a circuit diagram. Each component has its own standard symbol. If you imagine the switch being pushed so that it closes, it is clear from the diagram that there is a continuous path for the current to flow around the circuit.

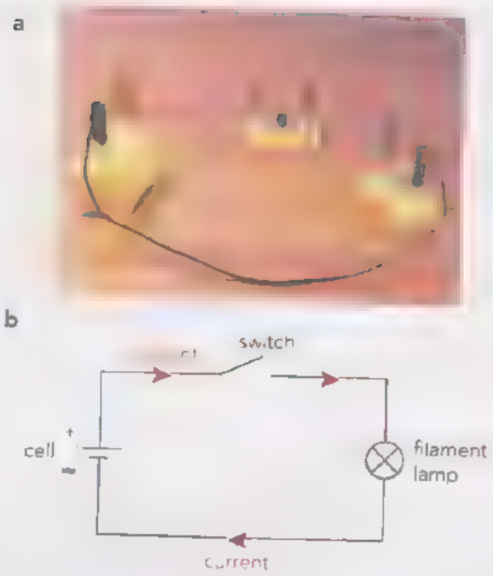


Figure 18.3a: A simple electric circuit, set up in a laboratory. **b:** The same circuit represented as a circuit diagram

It is obvious how the switch in Figure 18.3a works. You push the springy metal downwards until it touches the other metal contact. Then the current can flow through it. Most switches work by bringing two pieces of metal into contact with one another, though you cannot usually see this happening. It is worth having a look inside some switches to see how they work. (Of course, they must not be connected in a circuit when you examine them!)

Similarly, take a look at some filament lamps, like the one in Figure 18.3a. Every lamp has two metal contacts, for the current to flow in and out. Inside, one fine wire carries the current up to the filament (which is another wire), and a second wire carries the current back down again. Notice also how the circuit symbols for these and many other components have two connections for joining them into a circuit.

Good conductors, bad conductors

The wires we use to connect up circuits are made of metal because metals are good **conductors** of electric current. The metal is usually surrounded by plastic, so that, if two wires touch, the electric current cannot pass directly from one to another (causing a short circuit). Plastics (polymers) are good electrical **insulators**.

- Most metals, including copper, silver, gold and steel are good conductors.
- Polymers (such as Perspex® or polythene), minerals and glass are good insulators.

In between, there are many materials that do conduct electricity, but not very well. For example, liquids may conduct, but they are generally poor conductors.

People can conduct electricity – that is what happens when you get an electric shock. A current passes through your body and, if it is big enough, it makes your muscles contract violently. Your heart may stop, and you may get burns. Our bodies conduct because the water in our tissue is quite a good electrical conductor.

What is electric current?

When a circuit is complete, an electric current flows. Current flows from the positive terminal of the supply, around the circuit, and back to the negative terminal.

What is actually travelling around the circuit? The answer is electric charge. The battery or power supply in a circuit provides the push needed to make the current flow. This push is the same force that causes electric charges to attract or repel one another.

A current is a flow of electric charge. In a metal, the current is a flow of electrons. These are the negatively charged particles you learned about in Chapter 17.

conductor: a material that allows an electric current to flow through it

insulator: a material that makes it very difficult for an electrical current to flow through it

charge: carried around a circuit by the current; negative charge is carried by electrons

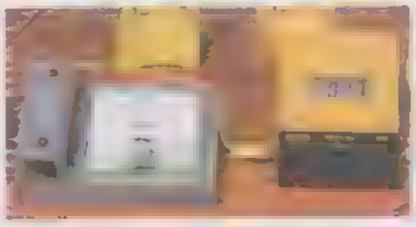


Figure 18.4: Ammeters measure electric current, in amps (A). There are two types: analogue (on the left) and digital (on the right).

Measuring electric current

To measure electric current, we use an ammeter. There are two types, as shown in Figure 18.4.

- An analogue meter has a needle, which moves across a scale. You have to make a judgement of the position of the needle against the scale.
- A digital meter gives a direct read-out in figures. There is no judgement involved in taking a reading.

A galvanometer is sometimes used instead of an ammeter when tiny currents need to be measured. It has a different circuit symbol – an upward pointing arrow to represent a needle. An ammeter is connected into a circuit in series, that is, between other components in the circuit. This circuit is called a series circuit, where components are connected in a line between other components. If the meter is connected the wrong way round, it will give negative readings. To add an ammeter to a circuit, the circuit must be broken (see Figure 18.5).

In a simple series circuit like the one shown in Figure 18.5, it does not matter where the ammeter is added, since the current is the same all the way round the series circuit. It does not get used up as it flows through the lamp or other components in the circuit.

The reading on an ammeter is in amperes (shortened to amps (A)), which is the SI unit of current. Smaller currents may be measured in milliamps (mA) or microamps (μA):

$$1\,\text{mA} = 0.001\,\text{A} = 10^{-3}\,\text{A}$$

$$1\,\mu\text{A} = 0.000\,001\,\text{A} = 10^{-6}\,\text{A}$$

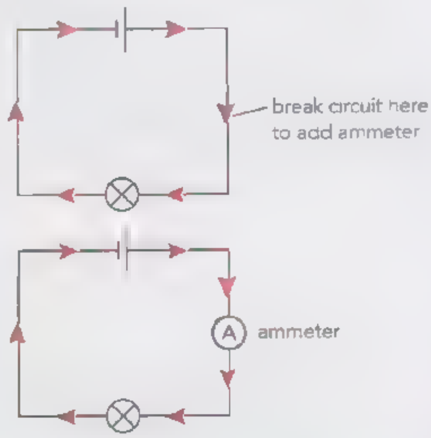


Figure 18.5: Adding an ammeter to a circuit. The ammeter is connected in series so that the current can flow through it.

KEY WORDS

galvanometer: a meter for measuring tiny electric current

ammeter: a meter for measuring electric current

ampere, amps (A): the SI unit of electric current

Questions

1. a What instrument is used to measure electric current?
   b How should it be connected in a circuit?
   c Draw its circuit symbol.
2. A circuit is set up in which a cell makes an electric current flow through a lamp. Two ammeters are included, one to measure the current flowing into the lamp, the other to measure the current flowing out of the lamp.
   a Draw a circuit diagram to represent this circuit.
   b Add an arrow to show the direction of the current around the circuit.
   c What can you say about the readings on the two ammeters?
3. a Name two materials that are good electrical conductors.
   b Name two materials that are good electrical insulators.

Two pictures: current and electrons

Metals are good electrical conductors because they [illegible]in electrons that can move about freely. (This has [illegible] been mentioned in Chapters 11 and 17.) The idea [illegible] in a bad conductor, such as most polymers, all of [illegible]ectrons in the material are tightly bound within the [illegible] or molecules, so that they cannot move. Metals [illegible]nt. While most of the electrons in a metal are [illegible] bound within their atoms, some are free to move within the material. These are called conduction [illegible] (see Figure 18.6). A voltage, such as that [illegible] by a battery or power supply, can start these [illegible]ion electrons moving in one direction through [illegible] and an electric current flows. Since electrons [illegible] negative electric charge, they are attracted to the [illegible] terminal of the battery.

Conventional electric current flows from positive to negative. Figure 18.7 shows the direction of the flow of charge around a simple circuit. We picture positive charge flowing out of the positive terminal, around the circuit and back into the cell at the negative terminal. Now, we know that in a metal it is the negatively charged electrons that move. They leave the negative terminal of the cell, and flow around to the positive terminal, in the opposite direction to the current. Hence we have two different pictures of what is going on in a circuit.

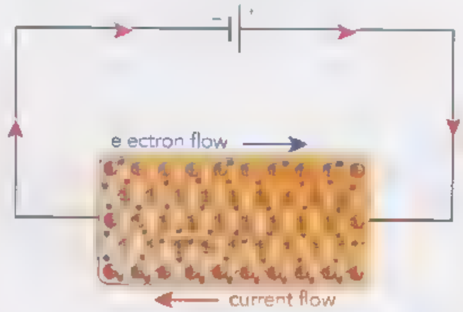


Figure 18.6: In a metal, some electrons are free to move about. In copper, there is one conduction electron for each atom of the metal. The atoms, having lost an electron, are positively charged. A battery pushes the conduction electrons through the metal. The force is the attraction between unlike charges that was discussed in Chapter 17.

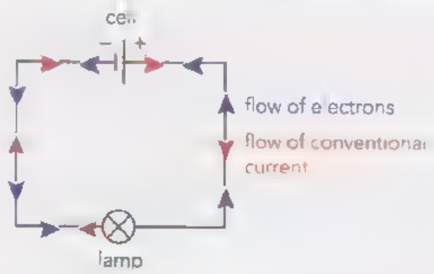


Figure 18.7: Two ways of picturing what happens in an electric circuit: conventional current flows from positive to negative; electrons flow from negative to positive.

We can think of conventional current, a flow of positive charge, moving from positive to negative. Conventional current is rather like a fluid moving through the wires, just like water moving through pipes. This picture does not tell us anything about what is going on inside the wires or components of a circuit. However, it is perfectly good for working out many things to do with a circuit.

what the voltage will be across a particular component, for example, or how much energy will be transferred to a particular lamp.

Alternatively, we can think of electron flow as, a movement of conduction electrons, from negative to positive. This picture can allow us to think about what is going on inside the components of a circuit, why a resistor gets warm when a current flows through it, for example, or why a diode allows current to flow in one direction only.

These two pictures are both models. The electron flow picture is a microscopic model, since it tells us what is going on at the level of very tiny particles (electrons). The conventional current picture is a macroscopic or large scale model.

The electrons in a circuit flow in the opposite direction to the electric current. It is a nuisance to have to remember this. It stems from the early days of experiments on static electricity. Benjamin Franklin realised that there were two types of electric charge, which he called positive and negative. He had to choose which type he would call positive. He chose to say that when amber was rubbed with a silk cloth, the amber acquired a negative charge. Franklin was setting up a convention, which other scientists then followed – hence the term 'conventional current'. He had no way of knowing that electrons were being rubbed from the silk to the amber, but his choice means that we now say that electrons have a negative charge. Remember that conventional current and electron flow move in opposite directions around a circuit.

Current and charge

An ammeter measures the rate at which electric charge flows past a point in a circuit. The electric current is defined as the charge passing a point in the circuit per unit of time (usually per second). We can write this relationship between current and charge as an equation using the quantities and symbols given in Table 18.1:

$$\text{current (A)} = \frac{\text{charge (C)}}{\text{time (s)}}$$

$$I = \frac{Q}{t}$$

$$\text{current} = \frac{\text{charge}}{\text{time}}$$

$$I = \frac{Q}{t}$$

Quantity	Symbol for quantity	Unit	Symbol for unit
current	I	amps	A
charge	Q	coulombs	C
time	t	seconds	s

Table 18.1: Symbols and units for some electrical quantities

So a current of 10 A passing a point means that 10 C of charge flows past that point every second. You may find it easier to recall this relationship in the following form.

charge (C) = current (A) × time (s)

$Q = It$

So, if a current of 10 A flows around a circuit for 5 s, then 50 C of charge flows around the circuit.

Worked Example 18.1 shows how to calculate the charge that flows in a circuit.

1 A current of 150 mA flows around a circuit for one minute. How much electric charge flows around the circuit in this time?

Step 1: Write down what you know, and what you want to know. Put all quantities in the units shown in Table 18.1.

$I = 150\ \text{mA} = 0.15\ \text{A}$ (or 150×10^{-3} A)

$t = 1\ \text{minute} = 60\ \text{s}$

$Q = ?$

Step 2: Write down an appropriate form of the equation relating Q, I and t. Substitute values and calculate the answer.

$Q = It$

$Q = 0.15\ \text{A} \times 60\ \text{s} = 90\ \text{C}$

Answer

90 coulombs of charge flow around the circuit.

Questions

4 a In which direction does conventional current flow around a circuit?

b In which direction do electrons flow around a circuit?

5 a What is the unit of electric current?

b What is the unit of electric charge?

6 a How many milliamps are there in 1 amp?
  b How many microamps are there in 1 amp?

7 Which of the following equations shows the correct relationship between electrical units?

$1\,A = 1\frac{C}{s}$ $\qquad$ $1\,C = 1\frac{A}{s}$

8 Calculate the missing values a–d in Table 18.2. Show all your working.

Charge	Current	Time
charge	current	time
220 C	2 A	a
57.6 C	b	3 hours
c	0.5 A	9 minutes
5.4 C	70 mA	d

Table 18.2

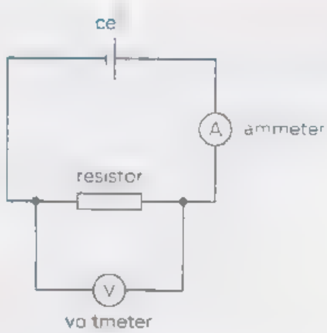


Figure 18.8: The cell provides the p.d. needed to push the current around the circuit. The amount of current depends on the p.d. and the resistance of the resistor. The ammeter measures the current flowing through the resistor. The voltmeter measures the p.d. across it. This circuit can therefore be used to find the resistance of the resistor. The ammeter is connected in series in the circuit. The voltmeter is connected in parallel in the circuit.

18.2 Voltage in electric circuits

Figure 18.8 shows a circuit in which a cell pushes a current through a resistor. The cell provides the **voltage** needed to push the current through the resistor. Here, 'voltage' is a rather loose term, and we should say that there is a **potential difference (p.d.)** across the resistor. Potential difference is defined as the work done by a unit charge passing through a component (a resistor, in this case). It is measured in **volts (V)** using a **voltmeter**. The p.d. is also the difference in electrical potential between two points: the point where the current enters a component and where it leaves a component. This is rather like the difference in height that makes a ball roll downhill.

Voltmeters are always connected in parallel with a component, that is, across a component. This circuit is called a parallel circuit, where components are connected in branches across the circuit. Voltmeters can either have an analogue display (with a needle) or a digital display (with a numerical value). The reading on a voltmeter is in volts (V) but they have different ranges. Smaller voltages can be measured in millivolts (mV) or microvolts (µV). Take care not to confuse italic, *V*, which is used as the symbol for an unknown potential difference or voltage, with upright, V, which is used as the symbol for the unit, volts. You can tell the difference in books, but you cannot always tell the difference when they are written.

There is a special name for the p.d. across a cell. It is called the **electromotive force (e.m.f.)** of the cell, and it is also measured in volts. The term can be misleading since e.m.f. is a voltage, not a force. Any component that pushes a current around a circuit is said to be a source of e.m.f., for example, cells, batteries, power supplies and dynamos. The e.m.f. is defined as the electrical work done by a source in moving a unit charge around a complete circuit.

voltage: the energy transferred or work done per unit charge, it can be imagined as the push of a battery or power supply in a circuit

potential difference (p.d.): the work done by (a unit) charge passing through an electrical component; another name for the voltage between two points

volts (V): the SI unit of voltage (p.d. or e.m.f.); 1 V = 1 J/C

voltmeter: a meter for measuring the p.d. (voltage) between two points

electromotive force (e.m.f.): the electrical work done by a source (cell, battery, etc.) in moving (a unit) charge around a circuit; the voltage across the terminals of a source

Questions

9 **a** What do the letters p.d. stand for?

b What meter is used to measure p.d.?

c Draw the symbol for this meter.

10 **a** What name is given to the p.d. across a cell or battery?

b What unit is this measured in?

Combining e.m.f.s

Many battery-operated electrical appliances need more than one cell to make them work. For example, a radio may need four 1.5 V cells. Each has an e.m.f. of 1.5 V and, when connected together in series, they give a combined e.m.f. of 6 V. You can see that, when cells are connected in series, their e.m.f.s add up.

Figure 18.9 shows some examples of this. In general, if cells with e.m.f.s E_1 and E_2 are connected in series, their combined e.m.f. E is given by:

$$E = E_1 + E_2$$

You can understand why e.m.f.s add up like this if you think about what happens when electric charge passes through. For four 1.5 V cells in series, each cell does electrical work on each unit charge as it passes through, so their combined e.m.f. must be 6 V.

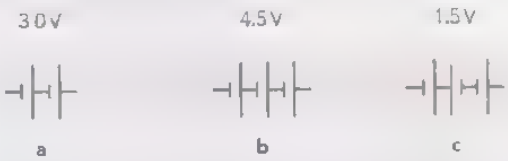


Figure 18.9: The e.m.f.s of cells or other supplies add up when they are connected in series. Here, each individual cell has an e.m.f. of 1.5V. **a, b:** More cells give a higher combined e.m.f. **c:** When one cell is connected the wrong way round, the combined e.m.f. is reduced.

Question

11 Three 12 V batteries are connected in series.

a Draw a diagram to show how these batteries could be connected to a lamp.

b Calculate the combined e.m.f. of the batteries.

What is a volt?

Why do we use high voltages for our mains supply? The reason is that a supply with a high e.m.f. does a lot of work on the charge that it pushes around the circuit. A 230 V mains supply does 230 J of work on each coulomb of charge that travels round the circuit.

This gives us a clue as to what we mean by a volt. A supply with an e.m.f. of 1 V does 1 J of work on each coulomb of charge it pushes round a circuit. In other words, a volt is a joule per coulomb.

The chemical energy supplied by the cell is what pushes electrons around a circuit. The e.m.f. tells you how much work is done on each coulomb of charge as it passes through the cell. This is described by the equation

$$\text{e.m.f. } (E) = \frac{\text{work done } \textit{on} \text{ the charge (J)}}{\text{charge (C)}}$$

The bigger the e.m.f. of a cell, the more strongly electrons are pushed around the circuit, just like pressure determines how strongly water is pushed through a pipe.

The potential difference across a device such as a lamp is a measure of how much electrical work is done by each coulomb as it passes through a component. This is described by the equation.

$$\text{p.d. } (V) = \frac{\text{work done } \textit{by} \text{ the charge (J)}}{\text{charge (C)}}$$

Both word equations above can be summarised as the word equation:

$$\text{voltage (V)} = \frac{\text{work done J}}{\text{charge C}}$$

Or, the symbol equation:

$$V = \frac{W}{Q}$$

[illegible]

$$\text{p.d.} = \frac{\text{work done by the charge}}{\text{charge}} \qquad V = \frac{W}{Q}$$

$$\text{e.m.f.} = \frac{\text{work done on the charge}}{\text{charge}} \qquad E = \frac{W}{Q}$$

The voltage or potential difference is the work done (or energy transferred) per unit charge.

As electric current flows through a circuit, the chemical energy of the cell is transferred to the components as internal energy (in a resistor) or kinetic energy (in a motor)

or transferred by light (in a lamp) and so on. Though we defined e.m.f. and p.d. in terms of work, we could have talked about the energy transferred instead. Recall from Chapter 8 that work done = energy transferred.

Questions

12 Rearrange the equation $V = \frac{W}{Q}$ to make:

- **a** W the subject of the equation
- **b** Q the subject of the equation.

13 Calculate the e.m.f. of a battery that gives 60 J of energy to a charge of 5 C.

14 The p.d. across a lamp is 12 V. The lamp is connected for 10 seconds. Calculate how many joules of energy are transferred when:

- **a** a charge of 1 C passes through it
- **b** a charge of 5 C passes through it
- **c** a current of 2 A flows.

Recall the equation that links charge, current and time.)

15 A circuit consists of two 1.5 V cells in series. How much energy does 2 C of charge gain on going through the cells?

16 A set of party lights consists of 20 identical lamps connected in series to a 240 V mains supply. What is the p.d. across each lamp?

17 **a** Draw a circuit consisting of a 1.5 V cell, a resistor and a lamp all in series. Arrange the cell so that conventional current flows clockwise round the circuit. Add a voltmeter across the cell. A charge of 6 C flows through the cell.

- **b** Calculate how much energy this amount of charge gains from the cell.
- **c** This amount of charge transfers 6 J of its energy to the lamp. What is the voltage across the lamp?
- **d** Work out the voltage across the resistor

The cake monster

How does energy travel from a cell to a lamp in a circuit? Figure 18.10 shows a model of how an electrical circuit works. During this activity, think carefully about how well it represents what goes on in an electric circuit.

A road runs through a factory that bakes cakes. Each truck on the road can carry only one cake. A cake monster can take only one bite out of a cake. The cake inspector (in the white laboratory coat) measures the 'cake difference' (p.d. for short), which is the amount a monster bites out of each cake. A traffic inspector (not shown) counts the number of trucks that pass him in a given time. The trucks return any uneaten cake to the factory

Figure 18.10

1 Copy and complete Table 18.3 to identify what each component (part) in the cake circuit represents in an electrical circuit.

Component	What it represents in an electric circuit
cake factory	
road	
truck	
cake monster	
cake inspector	
traffic inspector	

Table 18.3

2 How might you change the cake monster model to represent (show) the following changes in an electrical circuit:

- a increasing the number of lamps
- b a lamp with a bigger resistance.

CONTINUED

3 In the cake monster model of a series circuit, compare the 'cake difference' across the cake monster (or monsters) and the 'cake difference' across the cake factory.

Optional

4 Show how you would change the cake monster model to represent a parallel circuit. Using the model, explain why the current passing through the cell/battery is the sum of the currents passing through the individual branches of a parallel circuit.

The cake monster activity is a model for the way electric circuits work. Did it help you understand how a circuit works and give meaning to the different components? For example, did you get the idea that the cake represents energy that is being transferred from the factory (cell) to the monsters (lamps)? Can you suggest a better model for the way electric circuits work?

18.3 Electrical resistance

If you use a short length of wire to connect the positive and negative terminals of a cell (a battery) together, you can do a lot of damage. The wire and the cell may both get hot, as a large current will flow through them. There is very little electrical resistance in the circuit, so the current is large. The current flowing in a circuit can be controlled by adding components with electrical resistance to the circuit. The greater the resistance, the smaller the current that will flow.

Defining resistance

How much current can a cell push through a resistor? The electrical resistance of a component is measured in ohms (Ω). It is defined as the potential difference across the component divided by the current passing through it:

$$\text{resistance }(\Omega) = \frac{\text{potential difference(V)}}{\text{current(A)}}$$

$$R = \frac{V}{I}$$

The circuit shown in Figure 18.11 illustrates how we can measure the resistance of a resistor (or of any other component). We need to know the current flowing through the resistor, measured by the ammeter. We also need to know the p.d. across it, and this is measured by the voltmeter connected in parallel across it.

$$\text{resistance} = \frac{\text{p.d.}}{\text{current}}$$

$$R = \frac{V}{I}$$

resistance: a measure of how difficult it is for an electric current to flow through a device or a component in a circuit; it is the p.d. across a component divided by the current through it

ohm (Ω): the SI unit of electrical resistance; 1 Ω = 1 V/A

A voltmeter is always connected across the relevant component because it is measuring the potential difference between the two ends of the component.

- Ammeters are connected in series so that the current can flow through them.
- Voltmeters are connected in parallel to measure the p.d. across the component.

Worked Example 18.2 and Figure 18.11 show how to calculate the resistance of a resistor from measurements of current and p.d. Notice that we can show the current as an arrow entering (or leaving) the resistor. The p.d. is shown by a double-headed arrow to indicate that it is measured across the resistor. The resistance is simply shown as a label on or next to the resistor – it does not have a direction.

WORKED EXAMPLE 18.2

A resistor allows a current of 0.02 A to flow through it when there is a p.d. of 10.0 V between its ends. What is its resistance?

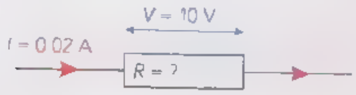


Figure 18.11: Sketch for diagram.

Step 1: Write down what you know, and what you want to know. You may prefer to write these quantities on a sketch of the situation (see Figure 18.11).

current $I = 0.02$ A

p.d. $V = 10.0$ V

resistance $R = ?$

Step 2: Write down the equation for R. Substitute values and calculate the answer.

$$R = \frac{V}{I}$$

$$= \frac{10.0\text{ V}}{0.02\text{ A}}$$

$$= 500\ \Omega$$

Answer

So, the resistance of the resistor is 500 Ω.

What is an ohm?

Let us think about the equation that defines what we mean by resistance:

We can see that it takes a p.d. of 10 V to make a current of 1 A flow through a 10 Ω resistor. It takes 20 V to make 1 A flow through a 20 Ω resistor, and so on. Hence resistance (in Ω) tells us how many volts are needed to make 1 A flow through that resistor. To put it another way, one ohm is one volt per amp.

$$\frac{V}{A}$$

In the case of Worked Example 18.2, it would take 500 V to make 1 A flow through the 500 Ω resistor.

Changing current

You can think of an electric circuit as an obstacle race. The current (or flow of charge) comes out of the positive terminal of the cell and must travel around the circuit to the negative terminal. Along the way, it must pass through the different components. The greater their resistance, the harder it will be for the charge to flow, and so the current will be smaller.

The greater the resistance in the circuit, the smaller the current that flows. However, we can make a bigger current flow by increasing the p.d. that pushes it. A bigger p.d. produces a bigger current. The greater the p.d. in a circuit (or across a component), the greater the current that flows.

Resistance and thickness

This idea of an obstacle race can help us to think about the resistance of wires of different shapes. A long, thin wire has more resistance than a short, fat one. Imagine an obstacle course that includes pipes of different sizes through which the runners have to pass. It is easy to get through a short pipe with a large diameter. It is much harder when the pipe is long and narrow.

- The longer a wire, the greater its resistance.
- The greater the diameter of a wire, the less its resistance.

Questions

18 **a** What is the resistance of a lamp if a current of 5.0 A flows through it when it is connected to a 240 V supply?

b When the p.d. across the lamp is increased, will the current flowing increase or decrease?

19 A student cuts two pieces of wire, one long and one short, from a reel.

a Which piece of wire will have the greater resistance?

b Draw a circuit diagram to show how you would check your answer by measuring the resistances of the two pieces of wire.

Measuring resistance

The circuit shown in Figure 18.12 can be used to find the resistance of a resistor. The circuit has a variable power supply, which can be adjusted to give several different values of p.d. For each value, the current is measured, and results like those shown in Table 18.4 are found. The last column in Table 18.4 shows values for R, calculated using $R = V/I$. These can be averaged to find the value of R.

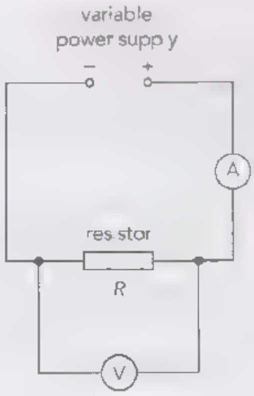


Figure 18.12: A circuit for investigating how the current through a resistor changes as the voltage across it varies. The power supply can be adjusted to give a range of values of p.d. (typically from 0 V to 12 V).

p.d. V/V	Current I/A	Resistance R/Ω
2.0	0.08	25.0
4.0	0.17	23.5
6.0	0.24	25.0
8.0	0.31	25.8
10.0	0.40	25.0
12.0	0.49	24.5

Table 18.4: Typical results for an experimental measurement of resistance

EXPERIMENTAL SKILLS

How length and thickness affects the resistance of a wire

Understanding how to measure resistance is really important because it introduces the measurements of voltage and current, which are essential for understanding circuits. In more sophisticated (complicated) circuits, resistance can change so that a device can respond to the environment (for example, a light can come on when it gets dark).

You will need:

- power supply
- 5 insulated (coloured) wires
- 2 crocodile clips
- metre ruler
- 2 lengths of resistance wire of different diameter
- masking tape
- heatproof mat to go underneath the resistance wire
- ammeter
- voltmeter.

CONTINUED

If a power supply is not available then use a suitable cell or series of cells but include a switch and only close the switch when you take measurements (to avoid draining the cell or battery). If two different gauges of wire are not available, lightly twist two lengths of the same gauge wire together to double the effective cross-section.

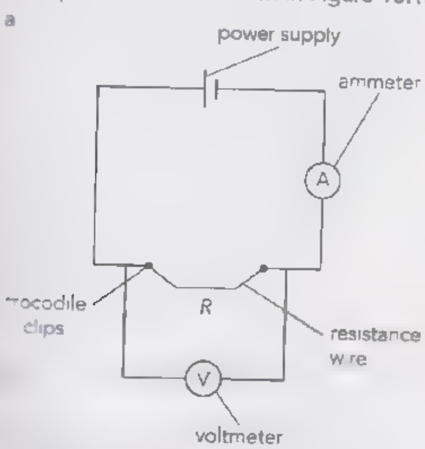
Safety: If the insulation on the wires melts or gives off poisonous fumes, reduce the voltage you use. Hot wires have the potential to burn skin. Avoid connecting the positive terminal of the power supply directly to the negative terminal (ensure that the current has to pass through the resistance wire). It may be necessary to place a resistor (fixed or variable) in series with the resistance wire in order to reduce the current through it. The voltages involved are too low to cause an electric shock.

Getting started

- State what devices you will use to measure voltage and current and describe how they should be wired into the circuit.
- What variable should be kept the same (control variable)?
- Why is it important to avoid taking measurements when the wire has zero length?
- Predict how the resistance of the wire will vary with the length of the wire.
- Predict how the resistance of the wire will vary with the diameter of the wire.
- Identify the independent and dependent variables.
- State two reasons why it is important to plot a graph of your results.
- You will be plotting a graph of your results. What should be plotted along on each axis?

Method 1

1 Set up the circuit as shown in Figure 18.13a. Set the power supply to 12V.



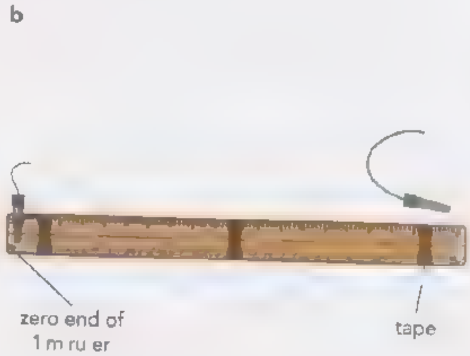


Figure 18.13a: Circuit diagram for the experiment. b: How to attach the wire to the ruler.

CONTINUED

2 Draw a table like Table 18.5, but remember to add more rows as you need them.

Length of resistance wire / cm	Current / A	Voltage / V	Resistance / Ω
Thin			
10			
20			
30			
Thick			
10			
20			
30			

Table 18.5

3 If your teacher has not already done so, attach the resistance wire along a metre ruler with insulating (or masking) tape at both ends and at the centre (see Figure 18.13b).

4 Put crocodile clips at the ends of the insulated (coloured) wires that will attach to the resistance wire.

5 Attach the first crocodile clip to the resistance wire where it crosses the 0.0 cm mark on the ruler and leave this in place throughout the experiment.

6 Attach the second crocodile clip where the resistance wire crosses the ruler at 10.0 cm and record the current and voltage values in the table.

7 Move the second crocodile clip at 10.0 cm intervals, each time recording the current and voltage values in the table.

8 Calculate the resistance values using $R = \frac{V}{I}$ and record the results in the table.

9 Plot a graph of resistance against length of the resistance wire (with the resistance along the horizontal axis) and label it 'thin'.

10 Repeat the experiment with thicker resistance wire (or loosely twist two wires of the same diameter together but, if you do, ensure the teeth of the crocodile clips are in contact with both wires). Plot the graph on the same axes for easy comparison and label it 'thick'.

Method 2

If you do not have access to resistance wires of fi[illegible] different diameters, twist wires of the sa[illegible] together. Keep the length of wire the same (say, 50 cm).

1 Use a micrometer to determine the diameter of the wire or look up the wire diameter corresponding to the SWG (standa[illegible] gauge) value on the reel that the w[illegible] from.

2 Use this information to work out the cross-sectional area of the wire or wires.

3 Using wires of the same length but increasing cross-section, record the voltage and current values, and calculate the resistance.

4 Plot a graph of resistance against the cross-sectional area.

5 Describe the relationship between resistance and cross-section.

6 How would you show that there is a[illegible] relationship?

CONTINUED

Questions

1 Copy each statement choosing the correct answer from the brackets.

a The resistance of a resistance wire {increases/decreases} when its length increases.

b The resistance of a resistance wire {doubles/halves} when its length doubles.

c This means that the resistance is {inversely/directly} proportional to its length. A straight-line graph passing through the origin will show this

d The resistance of a resistance wire {increases/decreases} when its diameter increases.

e The resistance of a resistance wire {doubles/halves} when its cross-sectional area doubles

f This means that the resistance is {inversely/directly} proportional to its cross-sectional area

2 Extrapolate your resistance against length graph (Method 1) towards the origin. What is the resistance when the length of the resistance wire is zero?

3 Use your answer to the previous question to suggest why a direct connection between the terminals of the power supply is not a good idea.

18.4 More about electrical resistance

The equation $R = \frac{V}{I}$ is used to calculate the resistance of a component in a circuit. We can rearrange the equation in two ways so that we can calculate current or p.d.:

$$I = \frac{V}{R} \qquad V = IR$$

So for example, we can calculate the current that flows through a 20 Ω resistor when there is a p.d. of 6.0 V across it. The current I is:

$$I = \frac{6.0\,\text{V}}{20\,\Omega} = 0.30\,\text{A}$$

Questions

Calculate the missing values **a–d** in Table 18.6. Show all your working.

Potential difference / V	Current / A	Resistance / Ω
240	2	**a**
12	**b**	3000
c	0.5	15
120	80	**d**

Table 18.6

21 **a** What p.d. is needed to make a current of 2.0 A flow through a 30 Ω resistor?

b Without calculation, what p.d. is required when the resistance is doubled?

22 **a** A p.d. of 240 V across a resistor causes a current of 80 mA to flow through it. What is the resistance of the resistor?

b What p.d. would cause a current of 40 mA to flow through the resistor?

23 What current flows when a p.d. of 7.5 V is connected across a 2 kΩ resistor?

Current–voltage characteristics

We can use the data shown in Table 18.4 to plot a graph of current against potential difference for a resistor. This graph is shown in Figure 18.14 and is known as a **current–voltage characteristic.**

- The p.d. V is on the x-axis, because this is the quantity we vary. It is the independent variable.
- The current I is on the y-axis, because this is the quantity that varies as we change V. It is the dependent variable.

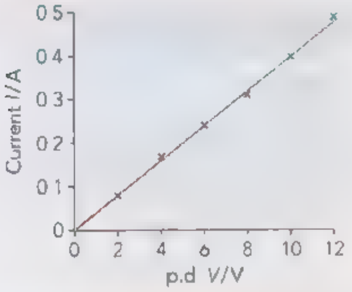


Figure 18.14: The current–voltage characteristic for the data in Table 18.4

In this case, the graph is a straight line that passes through the origin. This is what we expect because the equation $I = \frac{V}{R}$ shows that the current I is proportional to the p.d., V.

A resistor with a current–voltage characteristic like this is called an **ohmic resistor**. It is easy to predict the current that will flow through an ohmic resistor because the current is directly proportional to the p.d. across it. Double the voltage gives double the current, and so on.

Figure 18.15 shows what happens if we use a filament lamp instead of an ohmic resistor. You can see that the current–voltage characteristic for the filament lamp is curved.

Figure 18.15: The current–voltage characteristic for a filament lamp. The graph is not a straight line through the origin, showing that the lamp is not an ohmic resistor.

- At first, for low voltages, the graph is straight, showing that the current increases at a steady rate as the voltage is increased.
- At higher voltages, the graph starts to curve over. The current increases more and more slowly as the voltage is increased. Current is not proportional to voltage.

The graph shows that the lamp is not an ohmic resistor. Why is this? At first, when the voltage and current are small, the lamp behaves like an ohmic resistor. However, as the voltage increases, the current causes the filament to get hot and glow brightly. At high temperatures, the filament has a higher resistance and so the current does not increase as rapidly as it would do if the filament had remained cool.

This means that the resistance of the tungsten filament lamp increases as the current increases. But why does increasing the current make the tungsten hotter? This requires a more detailed explanation.

Increasing the current leads to an increase in the number of electrons flowing through the tungsten wire and this increases the number of collisions between the electrons and the lattice (the regular arrangement of atoms in the metal). Some of the kinetic energy from the electrons is transferred into internal energy, which makes the lattice vibrate more. This increases the resistance because it increases the number of collisions between the electrons and the lattice. In a similar way, it is more difficult to move through a crowd where people are moving in random directions compared to a crowd of people who are standing still.

current–voltage characteristic: a graph of current on the vertical axis and voltage on the horizontal axis

ohmic resistor: has a constant resistance; its I–V characteristic is a straight line, so that the current through it is directly proportional to the voltage across it

Figure 18.16 shows the typical shapes of the current–voltage characteristics for ohmic resistors, for a filament lamp and a diode. In Figure 18.16a, resistor Q has a higher resistance than resistor P. We can tell this because the current flowing through Q is always less than the current through P, for any voltage.

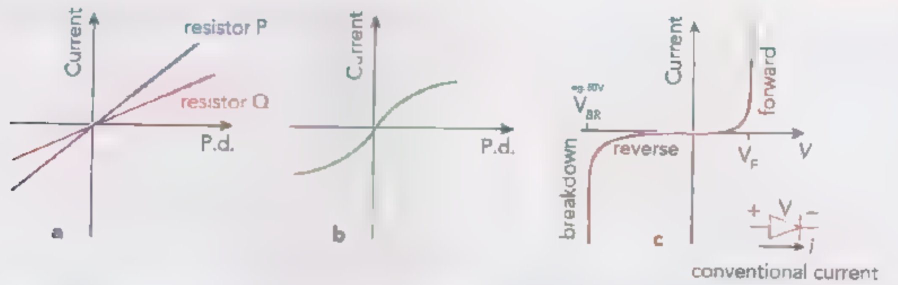


Figure 18.16: Typical current–voltage characteristics. **a:** For two ohmic resistors. **b:** For a filament lamp. **c:** For a diode.

Notice that these graphs show both positive and negative voltages. A negative current means one flowing in the opposite direction. This is achieved by connecting the cell or power supply the other way round. Figures 18.16a and b are symmetrical, showing that, whichever way round the components are connected, the current will be the same for a given voltage.

Figure 18.16c is the *I–V* characteristic of a diode, which is not symmetrical. A diode acts as a switch and only allows current to flow in one direction. The arrow on the diode symbol indicates the direction that conventional current can flow. A diode is a semiconductor so it behaves like both an insulator and a conductor. A diode behaves like an insulator until it is given enough voltage (energy per unit charge) to make it behave as a conductor. For a silicon diode this threshold voltage is 0.7 V.

Questions

24 Look at the graph shown in Figure 18.16a. How can you tell from the graph that the resistors are both ohmic?

25 Look at the graph shown in Figure 18.16b. How can you tell from the graph that the lamp's resistance increases as the p.d. across it increases?

Length and area

We have seen that the resistance of a wire depends on its length and its diameter. In fact, it is the cross-sectional area of the wire that matters.

- The resistance of a wire is proportional to its length.
- The resistance of a wire is inversely proportional to its cross-sectional area.

Suppose that we have a 4.0 metre length of wire. Its resistance is 100 Ω. What will be the resistance of a 2.0 metre length of wire with twice the cross-sectional area? Notice that making the wire shorter will reduce its resistance, and increasing its area will also reduce its resistance.

- Halving the length gives half the resistance = 50 Ω
- Doubling the area halves the resistance again = 25 Ω

Question

26 A 2.0 metre length of wire has a resistance of 4.0 Ω.

a What is the resistance of a piece of the same wire of length 20.0 metres?

b What is the resistance of a 4.0 metre wire with half the cross-sectional area, made of the same material?

18.5 Electrical energy, work and power

We use electricity because it is a good way of transferring energy from place to place. In most places, if you switch on an electric heater, you are getting the benefit of the energy released as fuel that is burned in a power station, which may be over 100 km away.

When you plug in an appliance to the mains supply, you are connecting up to quite a high voltage, something like 110 V or 230 V, depending on where you live. This high voltage is the e.m.f. of the supply. Recall that e.m.f. is the name given to the p.d. across an electrical source component such as a cell or power supply that pushes current around a circuit

By the principle of conservation of energy, the energy given to the charges by the cell must equal the sum of the energies given by the charges to the various components. This means that the e.m.f. across the cell is equal to the sum of the potential differences across all the components round the circuit. The total voltage across the cell equals the sum of the voltages across the lamps. This is something you will meet again in Chapter 19.

Batteries and power supplies give energy to the charges in a circuit. Similarly, we can think about other components in a circuit. For example, a small lamp may have a p.d. of 1.5 V across it. This means that each coulomb of charge does 1.5 J of electrical work to pass through the lamp and will transfer 1.5 J of energy to the lamp. Remember, work done is the same as energy transferred.

Electrical power

Most electrical appliances have a label that shows their power rating. An example is shown in Figure 18.17.

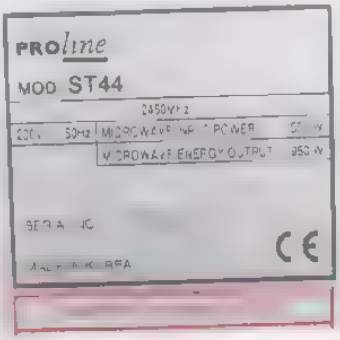


Figure 18.17: A label from the back of a microwave oven

Power ratings are indicated in watts (W) or kilowatts (kW). The power rating of an appliance shows the rate at which it transfers energy, and indicates the maximum electrical power the appliance draws from the mains supply when it is operating at full power.

Electrical power is the rate at which energy is transferred:

$$\text{power (W)} = \frac{\text{energy transferred (J)}}{\text{time taken (s)}}$$

$$P = \frac{\Delta E}{t}$$

electrical power: power = current × p.d. ($P = VI$)

The symbol, E, represents energy transferred. You should recognise this definition of power from Chapter 8.

This equation also reminds us of the definition of the unit of power, the watt: one watt is one joule per second.

1 W = 1 J/s

Voltage and energy

We have seen that the e.m.f. (voltage) of a supply tells us how much energy it transfers to charges flowing around the circuit. The greater the current flowing around the circuit, the faster that energy is transferred. Hence the rate at which energy is transferred in the circuit (the power, P) depends on both the e.m.f., E, of the supply and the current, I, that it pushes round the circuit. The following equation shows how to calculate the electrical power:

power (W) = current (A) × p.d. (V)

$$P = IV$$

power = current × p.d.

$$P = IV$$

You may prefer to remember this as an equation relating units:

watts = amps × volts

Calculating energy

Since energy transferred = power × time, we can use the equation $P = IV$ to give an equation for electrical energy transferred E in terms of current and voltage:

energy transferred (J) = current (A) × p.d. (V) × time (s)

$$E = IVt$$

energy transferred = current × p.d. × time

$$E = IVt$$

Worked Example 18.3 shows how to calculate the power of a device and how much energy is transferred in a given time.

An electric fan runs from the 230 V mains supply. The current flowing through it is 0.40 A. At what rate is electrical energy transferred by the fan? How much energy is transferred in one minute?

Step 1: First, we have to calculate the rate at which electrical energy is transferred. This is the power, P. Write down what you know and what you want to know

$V = 230\text{ V}$

$I = 0.40\text{ A}$

$P = ?$

Step 2: Write down the equation for power, which involves V and I, substitute values and solve.

$P = IV$

$P = 0.40\text{ A} \times 230\text{ V} = 92\text{ W}$

Step 3: To calculate the energy transferred in 1 minute, use $E = Pt$ (or $E = IVt$). Recall that time, t, must be in seconds.

$E = 92\text{ W} \times 60\text{ s} = 5520\text{ J}$

Answer

So, the fan's power is 92 W, and it transfers 5520 J of energy each minute.

Questions

27 Write down an equation linking watts, volts and amps.

28 Calculate the missing values a–d in Table 18.7. Show all your working.

[illegible]tage / V	Current / A	Power / P
240	2	**a**
12	**b**	60
c	0.5	15
120	80	**d**

Table 18.7

A 12 V power supply pushes a current of 6.0 A through a resistor. At what rate is energy transferred [illegible] the resistor?

A tropical fish tank is fitted with an electric heater, which has a power rating of 50 W.

The heater is connected to a 240 V supply. What current flows through the heater when it is [illegible]ned on?

[illegible] much energy is transformed by an electric [illegible] in an hour if a current of 20 mA flows through [illegible] when it is connected to a 120 V supply?

The equation $E = IVt$ could be used to calculate the chemical energy stored in a battery. A battery delivers a current at its rated voltage for a given time (until it discharges). The chemical energy stored in a battery can also be found by multiplying its charge by its rated voltage.

Units of electrical energy

Like other stores of energy, we could calculate the amount of energy transferred electrically in joules (J), but it is much more convenient to use kWh. This is because 1 kW = 1000 W and 1 h = 3600 s, so 1 kWh = 1000 W × 3600 s = 3.6×10^6 J (a big number). 1 kWh is sometimes called a unit of electricity. It is not, it is a unit of energy. It is kWh that are measured using an electricity meter, like the one shown in Figure 18.18.

a

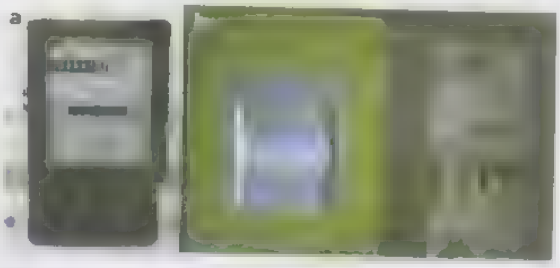


Figure 18.18a: An electricity meter. **b:** A typical smart electricity meter, which can be accessed remotely so that there is no need for someone to come to your house to read your meter.

All devices in homes have a power rating. For example, a fan heater might have a power output of 2 kW. If left running for two hours it would use 4 kWh (four units of electrical energy). This is easier to imagine than 1.44×10^7 J.

The equation for working out the number of units of electrical energy that are being used is:

$$\underset{(\text{kWh})}{\text{energy transferred}} = \underset{(\text{kW})}{\text{power}} \times \underset{(\text{hours})}{\text{time}}$$

Worked Example 18.4 shows how the number of units a device uses depends on how much power it transfers and the length of time it operates.

WORKED EXAMPLE 18.4

Marcus switches on a water heater for two hours. The power of the heater is 3.5 kW. How much energy is transferred in kWh (units)?

Step 1 Start by writing down what you know, and what you want to know.

power = 3.5 kW

time = 2 hours

energy transferred (kWh) = ?

Step 2: Now write down the equation for energy transferred in kWh.

energy transferred (kWh) = power (kW) × time (hours)

Step 3: Substitute the values of the quantities on the right-hand side and calculate the answer.

energy transferred (kWh) = 3.5 kW × 2 hours = 7 kWh

Answer

The water heater uses 7 kWh (or 7 units).

Worked Example 18.5 shows how to calculate the cost of electricity

WORKED EXAMPLE 18.5

Zara checks her electricity bill for a three month period. The meter reading at the start was 2531 kWh and at the end it was 2647 kWh. Electricity costs 16p per unit. What is her bill for electricity?

Step 1: Start by writing down what you know, and what you want to know.

metre reading at start = 2531 kWh

meter reading at end = 2647 kWh

cost per unit = 16p

units used = ?

total cost of electricity = ?

Step 2: Work out how many units were used.

Units used = 2647 kWh − 2531 kWh
= 116 kWh

Step 3: Now write down the equation for the total cost of electricity

total cost of electricity = number of units × cost per unit

Step 4: Substitute the values of the quantities on the right-hand side and work out the answer.

total cost of electricity = 116 kWh × 16 p = £18.56

Answer

Zara's bill is £18.56.

Questions

32 A 3 kW air conditioning unit used 216 kWh of electricity. Calculate how many days it was switched on for.

33 Eshan recorded the readings on his family's electricity meter at the beginning and end of one month. The readings were 990 987 and 991 013. Electricity costs 0.5 dirhams per unit. Calculate the cost of the electrical energy used by Eshan's family in this month.

34 Use the information in Table 18.8 to work out the missing values a–j. Assume that electricity costs 16p per unit.

Appliance	Power	Time	kWh / unit	Cost
desktop computer	**a**	3 hours	1.3	**b**
microwave oven	870 W	**c**	0.87	**d**
television	**e**	12 hours	1.0	**f**
energy efficient lamp	9 W	**g**	4.5×10^{-2}	**h**
kettle	2 kW	3 minutes	**i**	**j**

Table 18.8

PROJECT

Shining the light on what lamp to use

Design a public awareness and education campaign to persuade people to switch to using LED lamps.

Your campaign must include an eye-catching and scientifically-accurate poster or leaflet that can be understood by the public. One way to encourage people to read your leaflet is to provide a guide for choosing the correct bulb, including whether they need a screw or bayonet fitting.

You must include a table that compares the cost of the different light bulbs. This cost should include the purchase price plus the running cost over 20 years.

If you are working in pairs or small teams, you could also produce a podcast.

[illegible]

[illegible] people are already aware that energy-saving bulbs can reduce carbon emissions and save money. However, energy-saving light bulbs are more expensive to buy and some people think [illegible] the colour of light emitted by tungsten [illegible] prefer the look of the filament that can be [illegible] through the glass when the lamp is off (Figure [illegible]). Your campaign should emphasise that the output of energy-saving bulbs can match that [illegible] traditional tungsten filament bulb.

[illegible] saving light bulbs come in two varieties [illegible] fluorescent lamps (CFL) and clusters of light [illegible] diodes (LED). Older people remember LEDs when they produced quite a harsh light that was highly directional (sending out a beam of light in one direction). This was not suitable for lighting a room. LED lights have improved and some have even been made to look exactly like filament light bulbs. However, energy-saving light bulbs, particularly CFLs, contain electronic circuitry that is difficult to recycle. CFLs also contain mercury, which is toxic and a danger to health.

Figure 18.19: Different light bulbs. From left to right: LED, tungsten filament light, CFL.

People need to be educated to look for bulbs that give out the brightness they want (measured in lumens) instead of the power consumed (measured in watts). For example, a 60 W tungsten filament light bulb, a 14 W CFL and a 10 W LED all emit 850 lumens.

As part of the education campaign, you will need to compare the cost of using the different light bulbs all producing the same light output (say 850 lumens) and switched on for 25 000 hours over a period of

CONTINUED

20 years. In Table 18.9, we have assumed that the light bulbs all emit 850 lumens. When you research light bulbs, note that tungsten filament light bulbs are sometimes called incandescent light bulbs or halogen light bulbs. Only use the data in Table 18.9 if you really do not have time to research up-to-date numbers. By the time you read this book, CFLs and LEDs may have become even more efficient, they may last longer and the cost of electricity will certainly have changed.

	Type of bulb		
Quantity	Tungsten filament	CFL	LED
power rating	60 W	14 W	10 W
average cost per bulb (£)	1	2	4
average lifespan (hours)	1200	8000	25 000
number of bulbs needed for 25 000 hours			
total purchase price of bulbs over 20 years (£)			
Cost of electricity over 20 years when electricity costs £0.15 per unit (£)			
Total estimated cost over 20 years (£)			

Table 18.9: A table to work out the relative cost of the three different light bulbs.

Optional

Include explanations of how the lamps work. You already know how a tungsten filament light bulb works.

SUMMARY

An electric current will flow only if there is a supply of energy (for example, a battery) to push it around a complete circuit (that is, if there are no gaps in it).
Conductors (for example, metals) allow electric current to flow through them while insulators (for example plastic) resist the flow of current.
Current is a flow of electric charge (for example, electrons) in a circuit.
Electric current is measured in amperes or amps (A).
Current is measured with an ammeter connected into a circuit in series.
Conventional current flows from the positive terminal of a cell or battery to the negative terminal. Electrons flow in the opposite direction.
Current is the rate at which electric charge (for example, electrons) passes a point in a circuit: $I = \frac{Q}{t}$
Voltage or potential difference (p.d.) is like the difference in height that makes a ball roll downhill.
The p.d. across a cell is called the electromotive force (e.m.f.).
Voltage (and p.d. and e.m.f.) is measured with a voltmeter connected in parallel across the relevant component and they are all measured in volts (V).

CONTINUED

Voltage is the work done or energy transferred per unit charge given by the equation $V = \frac{W}{Q}$
The resistance of a component is measured in ohms (Ω).
The resistance of a circuit component is the p.d. across it divided by the current passing through it given by the equation $R = \frac{V}{I}$ and it can be found by experiment.
The resistance of a wire increases when it gets longer and resistance decreases as the diameter of the wire gets wider
The resistance of a wire is proportional to its length and inversely proportional to its cross-sectional area.
A current–voltage (I–V) characteristic is a graph with current plotted on the vertical axis and the voltage on the horizontal axis.
When the gradient of an I–V characteristic is smaller, the resistance is bigger.
The resistance of an ohmic resistor is constant because the current through it is directly proportional to the voltage across it. The I–V characteristic of an ohmic resistor is a straight line through the origin.
A filament lamp is an example of a component that is non-ohmic. As the current through the filament increases it gets hot and so its resistance increases.
Electric circuits transfer energy from the battery or power source to the circuit components and then the surroundings.
Electrical power is current multiplied by voltage ($P = IV$) and electrical energy is $E = IVt$.
The equation for working out the number of units of electrical energy being used is: Energy transferred (kWh) = power (kW) × time (hours)
The cost of electricity can be worked out using total cost of electricity = number of units × cost per unit

EXAM-STYLE QUESTIONS

1 Which of these non-metals can conduct electricity? **[1]**

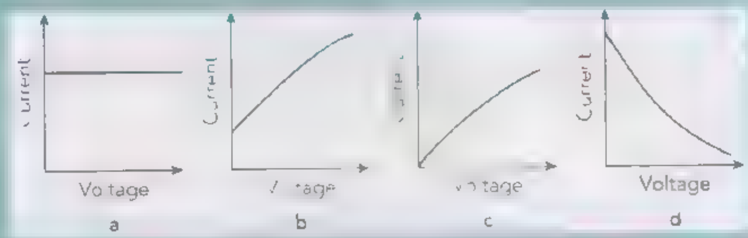
A plastic **B** chalk **C** carbon **D** rubber

2 Which of the following carries the current in a metallic conductor? **[1]**

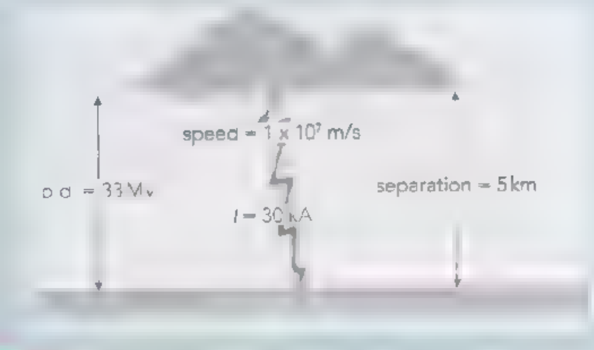
A negatively charged electrons
B negatively charged protons
C positively charged electrons
D positively charged protons

3 [illegible] charge a camera flash, a current of 400 mA flows from a 6.0 V battery [illegible] s. How much energy is transferred from the battery to the flash, approximately? **[1]**

A [illegible]4 J **B** 4 J **C** 1400 J **D** 4000 J



5 Charge separation between the ground and a cloud leads to a spark called lightning. When a lightning flash occurs, a current passes through the air. Use the data in this diagram to answer the questions.



a State the relationship between distance, speed and time. [1]

b Calculate the time it takes the lightning strike to cross the gap between the cloud and the ground. [2]

[Total: 11]

COMMAND WORDS

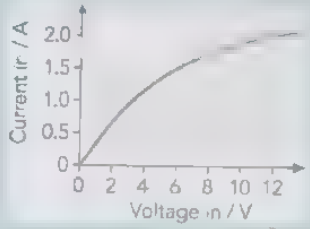
state: express in clear terms

calculate: work out from given facts, figures or information

6 A student wants to measure the resistance of filament lamp. She used an ammeter, a battery, a lamp and a voltmeter

a Draw the circuit she built. [2]

b The student obtains the graph below for the filament lamp.



i Use the graph to find the current through the filament lamp when the voltage is 6.0 V. [1]

ii State the relationship between voltage, current and resistance. [1]

iii Calculate the resistance of the lamp when the voltage is 6.0 V ... the unit [3]

[Total: 9]

give: produce an answer from a given source or recall / memory

explain: set out purposes or reasons / make the relationships between things evident / provide why and / or how and support with relevant evidence

LF-EVALUATION CHECKLIST

...studying this chapter, think about how confident you are with the different topics. This will help you see ...gaps in your knowledge and help you to learn more effectively.

		Needs more work	Almost there	Confident to move on
... what is required for an electric current to ... a circuit.	18.1			
...guish between conductors and insulators from a ... and give examples of each	18.1			
... what a current is made of	18.1			
... the units of current, voltage and resistance	18.1, 18.2 18.3			
...ecall what devices measure current and voltage and know how to connect them into a circuit.	18			
...ut the direction that electrons flow around a ... and recall that this is opposite to the direction of ...tional current	18.1			
...and what a current is and recall and use the ... that relates current, charge and time.	18.1			

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Recall the name given to the voltage across a cell or battery	18.2			
State the units of electromotive force (e.m.f.) and potential difference (p.d.)	18.2			
Show an understanding of what e.m.f. is (not what it stands for).	18.2			
Recall the name of the unit that resistance is measured in.	18.3			
Recall the equation that relates resistance, current and voltage.	18.3			
Understand how changes in resistance and voltage affect current.	18.3			
Describe an experiment to determine resistance using a voltmeter and ammeter	18.3			
Relate the resistance of a wire to its length and diameter (without doing any calculations).	18.3			
Recall and use the relationships that relate the resistance of a wire to its length and cross-sectional area.	18.3			
Understand how the gradient of a current-voltage characteristic relates to resistance.	18.4			
Sketch and explain the current–voltage (I–V) characteristics of an ohmic resistor and a filament lamp.	18.4			
Understand that electric circuits transfer energy from the battery or power source to the circuit components and then the surroundings.	18.5			
Recall and use the equations for electric power and energy.	18.5			
Calculate electrical energy in kWh and work out its cost.	18.5			

Chapter 19

Electrical circuits

...and interpret circuit diagrams

...e how current and resistance vary in different circuits

... the hazards of using electricity and describe and explain electrical safety measures including ...it-breakers and earth wires

GETTING STARTED

Spend two minutes thinking about these questions before comparing notes with the person sitting next to you. Add to, or correct, your own work. Be prepared to share your thoughts with the class.

How can you tell a series circuit apart from a parallel circuit?

Using what you remember from Chapter 18 about how the resistance of a wire depends on its length and diameter, try answering the following questions:

- Why does less current flow when there are two lamps in series?
- Why does more total current flow when there are two lamps in parallel?

HOW CLOSE ARE WE TO CREATING ARTIFICIAL INTELLIGENCE?

In Chapter 18 we met Alessandro Volta. In 1800 he invented the first battery and the first electric circuit. Development of the first electric light bulb followed almost immediately, though it was almost a century before it was good enough to sell. Electric lighting became the first of many applications of electric circuits. For example, electric circuits can transport electricity from where it is generated to where it is used (see Chapters 7 and 21). As we will see later in this chapter, circuits can also be used to automate tasks, like switching on a lamp when it gets dark, and transferring energy in a light bulb in the process.

The semiconductor transistor is perhaps the most important invention of the last century because it is much smaller and cheaper than the device (called a valve) that it replaced. Without transistors we would not have smartphones or personal computers as these are based on miniature electric circuits that use millions of transistors. If smartphones were made using the old technology, they would fill a room. Making computers smaller means they can be used to control more appliances.

Driverless cars will be controlled by computers, which will make decisions based on programs written by people. However, an alien might think the cars are automatons (making decisions by themselves). Robots (Figure 19.1) already exist that could be mistaken for artificial intelligence (machines that can think for themselves). Some scientists worry that we are close to creating artificial intelligence, perhaps by accident, which might be a threat to our future existence. Science fiction movies like *Ex Machina* paint a bleak future.

Figure 19.1: Rico's combat robot from the science fiction film, *Judge Dredd*, 1995

Discussion questions

1. Draw a table with two columns. In the left column, write down the names of ten household appliances (such as 'television') that rely on electricity, and, therefore, include an electric circuit. In the right-hand column, write down the names of appliances that do not need electricity. What do you notice?
2. Try describing our world if electricity had not been discovered.
3. What are the potential positives and negatives of automation and artificial intelligence?

19.1 Circuit components

Figure 19.2 shows the circuit symbols for the electrical components that you are most likely to meet in this course. You should try to remember them. A complete list is given in the appendix at the end of the book. The symbols in blue are supplementary content.

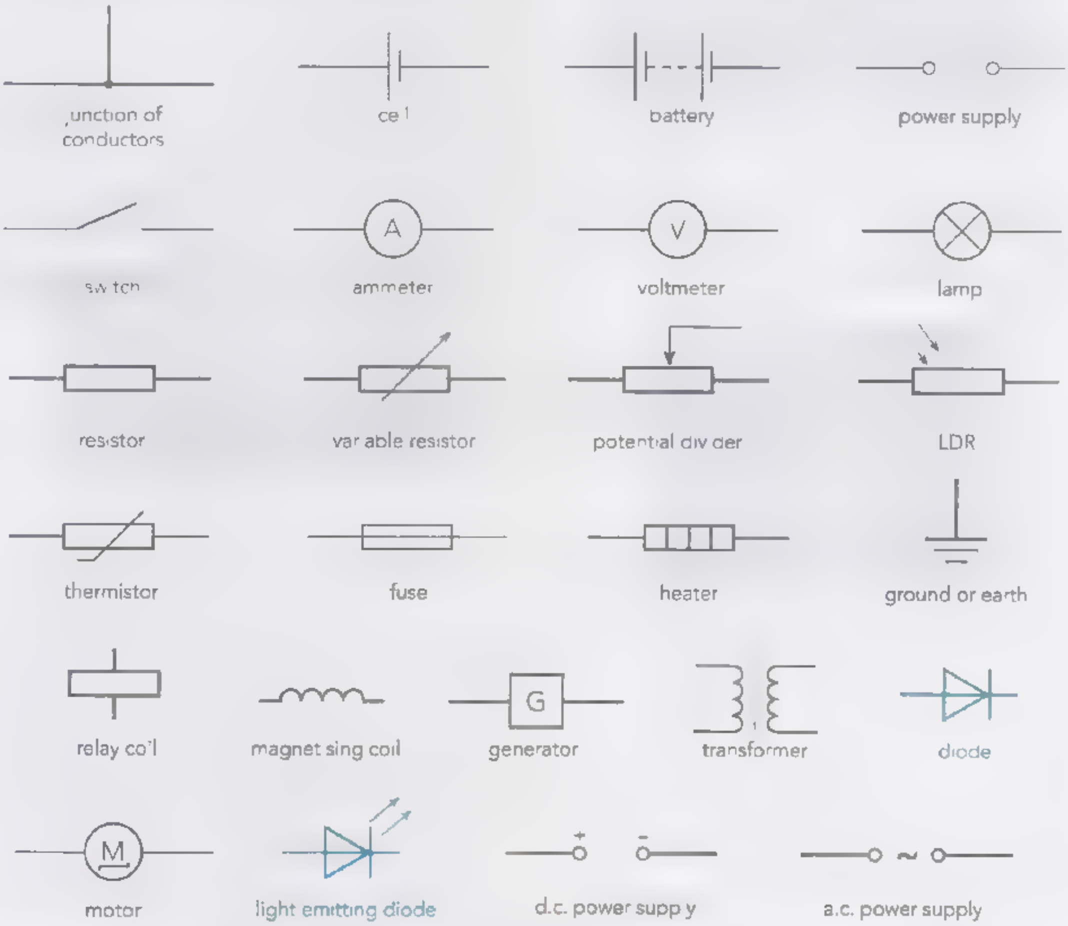


Figure 19.2: Circuit symbols for electrical components

Resistors

A **resistor** (Figure 19.3) can be used to control the amount of current flowing around a circuit. A resistor has two terminals, so that the current can flow in one end and out the other. They may be made from metal wire (usually an alloy – a mixture of two or more metals with a high resistance) or from carbon. Carbon (like the graphite in a pencil) conducts electricity, but not as well as most metals. Hence high-resistance resistors tend to be made from graphite, particularly as it has a very high melting point.

resistor: a component in an electric circuit whose resistance decreases the current flowing

Figure 19.3: A selection of resistors. Some have colour-coded stripes to indicate their value, and others use a number code.

A **variable resistor** can be used to alter the current flowing in a circuit. Figure 19.4a shows the inside of a variable resistor – notice that it has three terminals.

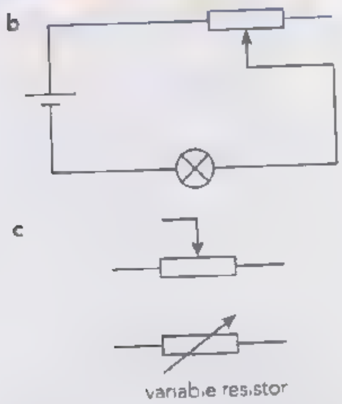


Figure 19.4a: A variable resistor. The resistance is provided by a track of resistive wire or carbon. The resistance in the circuit depends on the position of the sliding contact. **b:** The current flowing around this circuit depends on the position of the slider on the variable resistor. Imagine sliding the arrow to the right. The current will then have to flow through more resistance, and so it will decrease. **c:** Symbols for a variable resistor

As the control is turned, the contact slides over the resistive track. The current enters at one end and flows through the track until it reaches the contact, where it leaves the resistor. The amount of track that it flows through depends on the position of the contact. Variable resistors like this are often used for the volume control of a radio or stereo system. (You may have come across a rheostat, which is a laboratory version of a variable resistor.)

Figure 19.4b shows an example of a circuit that contains a variable resistor, and Figure 19.4c shows two different circuit symbols for a variable resistor. Note that the upper symbol has three terminals (like the resistor itself), but this circuit only makes use of two of them

variable resistor: a resistor whose resistance can be changed, for example by turning a knob or moving a slider

light-dependent resistor (LDR): a device whose resistance decreases when light shines on it

Light-dependent resistors

A **light-dependent resistor (LDR)** is a type of variable resistor whose resistance depends on the amount of light falling on it (Figure 19.5). An LDR is made of a material that does not normally conduct well. In the dark, an LDR has a high resistance, often over 1 MΩ. However, light can provide the energy needed to allow a current to flow. Shine light on an LDR and its resistance decreases. In bright light, its resistance may decrease to 400 Ω

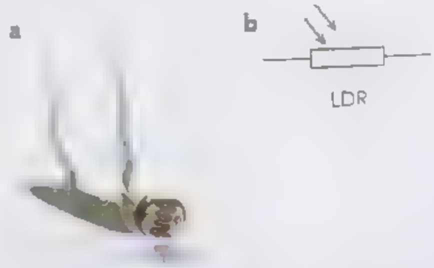


Figure 19.5a: A light-dependent resistor. The interlocking silver fingers are the two terminals through which the current enters and leaves the resistor. In between (black-coloured) is the resistive material. **b:** In the circuit symbol, the arrows represent light shining on the LDR.

LDRs are used in circuits to detect the level of light, for example in security lights that switch on automatically at night. Some digital clocks have one fitted. When the room is brightly lit, the display is automatically brightened so that it can be seen against its bright surroundings. In a darkened room, the display need only be dim.

Thermistors

A thermistor (Figure 19.6) is another type of resistor whose resistance depends on its environment. In this case, its resistance depends on its temperature. The resistance changes by a large amount over a narrow range of temperatures.

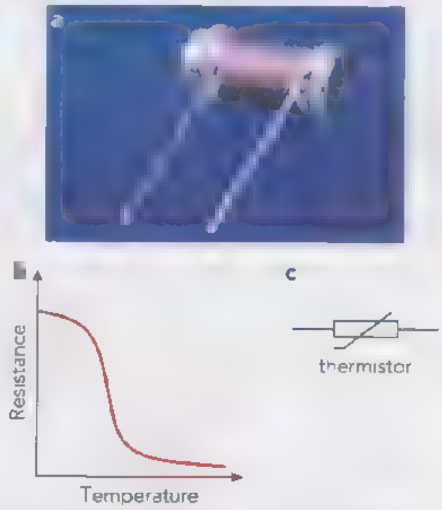


Figure 19.6a: A thermistor **b:** The resistance of a thermistor depends on the temperature. In this case, in the middle of the curve, its resistance drops a lot as the temperature increases by a small amount **c:** In the circuit symbol, the line through the resistor indicates that its resistance is not fixed but depends on an external factor (in this case, the temperature).

For **NTC thermistors**, the resistance decreases as they are heated, perhaps from 2 kΩ at room temperature to 20 Ω at 100 °C. NTC stands for negative temperature coefficient. These thermistors are useful for temperature probes – see the discussion of thermometers in Section 9.4.

Questions

1 a Draw the circuit symbol for a resistor.
  b Draw the circuit symbol for a variable resistor.

2 a What does LDR stand for?
  b Draw its circuit symbol.
  c What happens to the resistance of an LDR when light is shone on it?

3 a Draw the circuit symbol for a thermistor.
  b Give one use for a thermistor.
  c Explain why a thermistor is suitable for the use you chose in **b**.

Relays

A **relay** is a type of switch that works using an electromagnet. Figure 19.7 shows that, when a relay is used, there are two circuits:

- the magnetising coil (electromagnet) of the relay is in one circuit
- the switch is in the other circuit.

When a current flows through the relay or magnetising coil in the first circuit, it becomes magnetised (Figure 19.7). It pulls on the switch in the second circuit, causing it to close, and allowing a current to flow in the second circuit to turn on a motor. This will be shown in more detail in Chapter 20.

The second circuit often involves a large voltage, which would be dangerous for an operator to switch, or which could not be switched by a normal electronic circuit (because these work at low voltage). Remember, when a relay is used, there are two complete circuits.

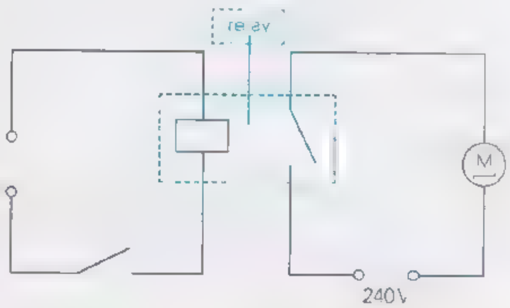


Figure 19.7: A relay circuit

NTC thermistor: a resistor whose resistance decreases with increasing temperature

relay: a switch controlled by an electromagnet

Sensing circuits

A relay can be used in a circuit that senses changes in temperature or light level. Figure 19.8 shows a circuit that will turn on a lamp when the temperature rises. This would be useful, for example, in an industrial freezer. If the freezer fails, a large quantity of frozen food could be ruined. Here is how the circuit in Figure 19.8 works:

- When the temperature is low, the thermistor has a high resistance. The current in the left-hand circuit is small, so the relay remains open. There is no current in the right-hand circuit
- When the temperature rises, the resistance of the thermistor decreases. The current through the relay coil increases, pulling the relay switch closed. Now a current flows in the right-hand circuit and this makes the lamp light

This circuit could be adapted to detect changes in light level. For example, the lights in a museum are switched off at night. A thief might use a torch and this could be detected using a light-dependent resistor in place of the thermistor.

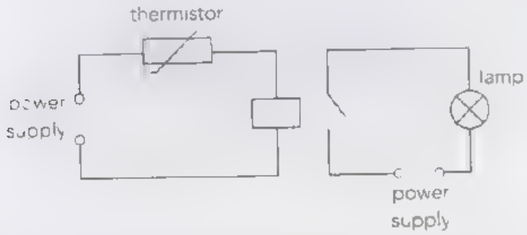


Figure 19.8: An alarm circuit that uses a relay.

Question

4 a Redraw the circuit shown in Figure 19.8 so that a heater only comes on in the daytime. Include a light-dependent resistor in place of the thermistor and a heater in place of the lamp.

b Explain why the heater would be cold when the LDR is in darkness.

c Explain why the heater would be hot when light shines on the LDR

Diodes

A **diode** is a component that allows electric current to flow in one direction only. Its circuit symbol (Figure 19.9a) represents this by showing an arrow to indicate the direction in which current can flow. Remember that the arrow in the diode symbol shows the direction in which conventional current can flow through the diode. The bar shows that current is stopped if it tries to flow in the opposite direction. It can help to think of a diode as being a 'waterfall' in the circuit (Figure 19.9b). Charge can flow over the waterfall, but it cannot flow in the opposite direction, which would be uphill. Some diodes give out light when a current flows through them (Figure 19.9c). A diode that does this is called a **light-emitting diode (LED)**. Again, it can help to think of the waterfall. As the charge flows over the waterfall, some of the energy it loses is given out as light.

Light-emitting diodes are familiar in many pieces of electronic equipment. For example, they are used as the small indicator lights that show whether a stereo system or television is on. Modern traffic lights often use arrays of bright, energy-efficient LEDs in place of filament bulbs. These LED arrays use very little power, so they are much cheaper to run than traditional traffic lights. Also, they require little maintenance, because, if one LED fails, the remainder still emit light

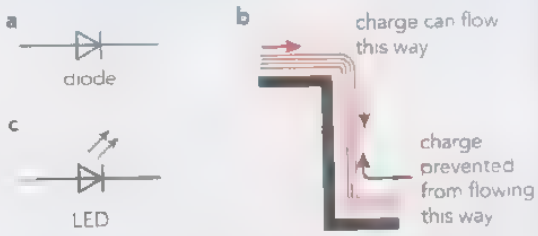


Figure 19.9a: Circuit symbol for a diode. A diode allows current to flow in one direction only, in the direction of the arrow. **b:** A diode is like a waterfall. Charge can flow downhill, but is prevented from flowing back uphill. **c:** Circuit symbol for a light emitting diode. The arrows represent the light that is emitted when a current flows through it.

diode: an electrical component that allows electric current to flow in one direction only

light emitting diode (LED): a type of diode that emits light when a current flows through it

Questions

5 A diode will allow an electric current to flow in one direction only. Using a lamp, battery and diode, draw a circuit diagram in which:

a the lamp lights

b the lamp does not light.

6 A friend wants to produce the I–V characteristic of a diode. Draw the circuit diagram that he will need to build.

19.2 Combinations of resistors

If you have two resistors, there are two ways they can be connected together in a circuit: in series and in parallel. This is illustrated for two 10 Ω resistors in Figure 19.10. It is useful to be able to work out the total resistance of two resistors like this. What is their combined resistance or effective resistance?

For the two 10 Ω resistors in series in Figure 19.10a, the current has to flow through two resistors instead of one. The resistance in the circuit is doubled, so the combined resistance is 20 Ω.

For the two 10 Ω resistors in parallel in Figure 19.10b, there are two possible paths for the current to flow along, instead of just one. The resistance in the circuit is halved, so the effective resistance is 5 Ω.

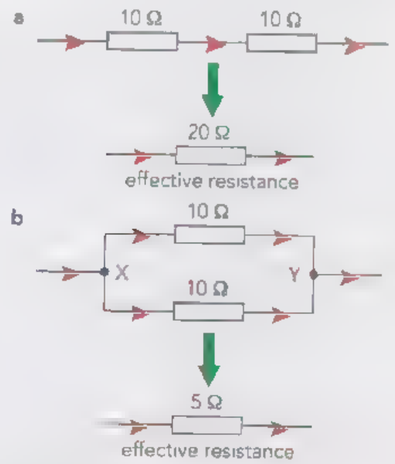


Figure 19.10: Two ways of connecting two resistors in a circuit. **a:** In series. **b:** In parallel.

We have not really proved these values for the combined or effective resistance, but you should see that they are reasonable values.

To recognise when two resistors are connected in series, trace the path of the current around the circuit. If all the current flows through one resistor and then through the other (as in Figure 19.10a), the resistors are connected in series. They are connected end-to-end. For resistors in parallel, the current flows differently.

It flows around the circuit until it reaches a point where the circuit divides (as at point X in Figure 19.10b). Then some of the current flows through one resistor, and some flows through the other. Then the two currents recombine (as at point Y in Figure 19.10b) and return to the cell. Resistors in parallel are connected side-by-side.

Resistors in series

If several resistors are connected in series, then the current must flow through them all, one after another. The combined resistance, R, in the circuit is simply the sum of all the separate resistances. For three resistors in series (Figure 19.11a), the equation for their combined resistance is:

$$R = R_1 + R_2 + R_3$$

Figure 19.11b shows the same current, I, flowing through three resistors. Remember, current cannot be used up because charge is conserved. We can calculate the combined resistance for this circuit:

combined resistance = 10 Ω + 20 Ω + 20 Ω = 50 Ω

So the three resistors could be replaced by a single 50 Ω resistor and the current in the circuit would be the same.

So, for resistors in series:

- the combined resistance is equal to the sum of the resistances
- the current is the same at all points around the circuit
- the bigger the resistance, the bigger the p.d. across it.

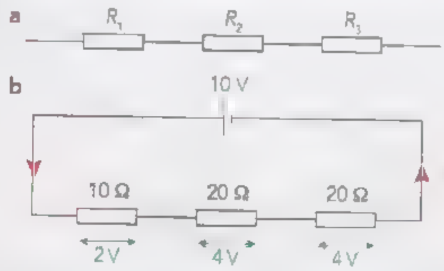


Figure 19.11a: Three resistors connected in series. **b:** Values of current and p.d. in a series circuit. The same current, I, flows through each of the three resistors.

When the current through an electrical conductor is constant, the p.d. across it will increase when its resistance increases. For example, as long as the combined resistance of the three resistors in Figure 19.11b is kept the same, the current at every point in the series circuit will remain the same. However, there is a bigger p.d. across the bigger resistors. In fact, the p.d. is proportional to resistance. The p.d. across the 20 Ω resistors is double the voltage across the 10 Ω resistor. If the three resistors were replaced by one 50 Ω resistor then there would be a p.d. of 10 V across it (equal to the cell voltage). It might seem odd to think of conductors having resistance but even the best conductors have resistance (although superconductivity – conduction with zero resistance – is an area of active research).

Resistors in parallel

The lights in a conventional house are connected in parallel with one another. The reason for this is that each one requires the full voltage of the mains supply to work properly. If they were connected in series, the p.d. would be shared between them and they would be dim. In parallel, each one can be provided with its own switch, so that it can be operated separately. If one lamp fails, the others remain lit.

The effective resistance of several resistors connected in parallel is less than that of any of the individual resistors. This is because it is easier for the current to flow. You can see this for two resistors in parallel in Figure 19.12a. The current flowing from the source divides up as it passes through the resistors. Figure 19.12b shows the current from the power supply splitting up and passing through two resistors in parallel.

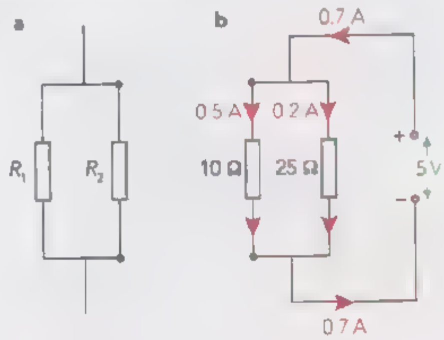


Figure 19.12a: Two resistors connected in parallel. **b:** Values of current and p.d. in a parallel circuit. The current flowing from the supply is shared between the resistors.

So, for two resistors in parallel:

- the effective resistance is less than the resistance of either resistor
- the current from the source is greater than the current through either resistor.

Questions

7 What are the advantages of connecting lamps in parallel in a lighting circuit?

8 Three resistors are connected in series with a battery, as shown in Figure 19.13.

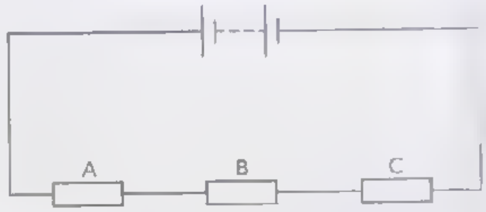


Figure 19.13

Resistor A has the greatest resistance of the three. The current through A is 1.4 A. What can you say about the currents through B and C?

9 What is the combined resistance of three 30 Ω resistors connected in series?

Voltage in series circuits

When resistors are connected in series with each other in a circuit with a power supply, there is a p.d. across each resistor. From the numerical example shown in Figure 19.11b, you can see that adding up the p.d.s across the three separate resistors gives the p.d. of the power supply. In other words, the p.d. of the supply is shared between the resistors. We can write this as an equation:

$V = V_1 + V_2 + V_3$

Festive lights, such as those used to celebrate different festivals, are often wired together in series. This is because each bulb works on a small voltage. If a single bulb was connected to the mains supply, the p.d. across it would be too great. By connecting them in series, the mains voltage is shared out between them. There is a disadvantage: if one bulb fails (its filament breaks), they all go out. This is because there is no longer a complete circuit for the current to flow around.

Three 5 0 Ω resistors are connected in series with a 2 V power supply Calculate the combined resistance of the three resistors, the current that flows in the circuit, and the p.d across each resistor

Step 1: Draw a circuit diagram and mark on it all the quantities you know Add arrows to show how the current flows (Figure 19.14)

Figure 19.14: Sketch diagram.

Step 2: Calculate the combined resistance.

[illegible]

$R = 5\,0\,\Omega + 5\,0\,\Omega + 5\,0\,\Omega$

$R = 15\,\Omega$

Step 3: Calculate the current flowing. A p.d. of 12 V is pushing current through a resistor of 15 Ω total resistance So:

current $I = \frac{[illegible]}{R}$

[illegible]

Step 4: Calculate the p.d. across an individual 5 0 Ω resistor when a current of 0 8 A flows through it.

p.d. $V = IR = 0\,8\text{ A} \times 5\,0\,\Omega = 4.0\text{ V}$

Note that the 12 V of the supply is shared out equally between the resistors, since each has the same resistance. So, we could have worked out the p.d across an individual resistor without knowing the current (12 V ÷ 3 = 4 V)

Answer

The combined resistance of the three resistors is 15 Ω, the current that flows in the circuit is 0.8 A, and the p.d across each resistor is 4.0 V

Question

10 One 4 Ω resistor and one 6 Ω resistor are connected in a series circuit with a 6 V power supply. Calculate:

a the combined resistance of the two resistors

b the current that flows in the circuit

c the p.d. across each resistor

Potential divider circuits

Often, a power supply or a battery provides a fixed potential difference. To obtain a smaller p.d , or a variable p.d., this fixed p.d must be split up using a circuit called a **potential divider** Figure 19 15 shows two forms of potential divider

potential divider part of a circuit consisting of two resistors connected in series to obtain a smaller voltage than supplied

In the circuit shown in Figure 19 15a, two resistors R_A and R_B are connected in series across the 6 V power supply The p.d. across the pair is thus 6 V (It helps to think of the bottom line as representing 0 V and the top line as 6 V. The p.d. at point X, between the two resistors, will be part-way between 0 V and 6 V depending on the values of the resistors If the resistors are equal the p.d at X will be 3 V. The p.d. of the supply will have been divided in half, hence the name 'potential divider'

To produce a variable output, we replace the two resistors with a variable resistor, as shown in Figure 19.15b. By altering the resistance of the variable resistor, the voltage at X can have any value between 0 V and 6 V

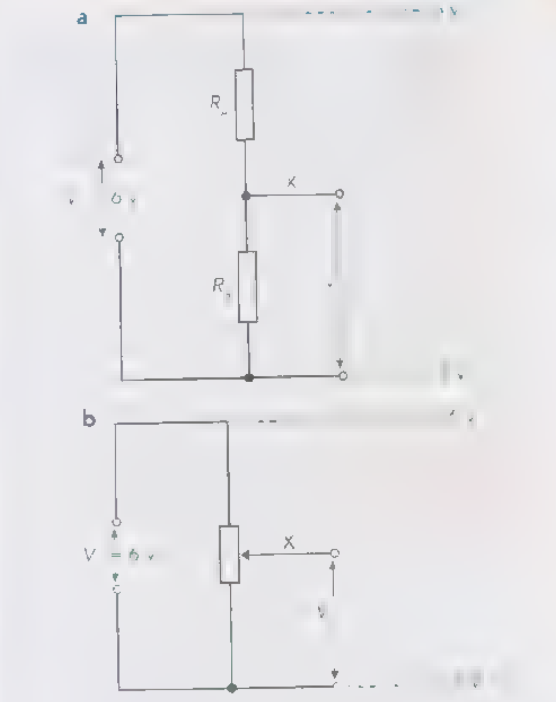


Figure 19.15a: A simple potential-divider circuit. The output voltage is a fraction of the input voltage. The input voltage is divided according to the relative values of the two resistors. **b:** A variable resistor is used to create a potential divider circuit, which gives an output voltage that can be varied.

Question

11 a Two resistors are going to be connected to form a potential divider circuit. Should they be connected in series or in parallel with each other?

b State briefly the function of a potential divider circuit.

Normally, when the resistance of an electrical conductor is increased, the current through it decreases. However, the current through a pair of resistors will be constant if their total resistance is constant. If the resistance of one resistor is increased, the resistance of the other resistor has to be decreased to maintain the same total resistance and the same constant current. The p.d. will be bigger across the bigger resistor. This is what is happening in Figure 19.15b. The current through the variable resistor is constant but the resistance (and the voltage) above and below X changes.

More about potential divider circuits

In the circuit shown in Figure 19.16a, the p.d. across the lamp is equal to the e.m.f. across the cell (that is, 9 V).

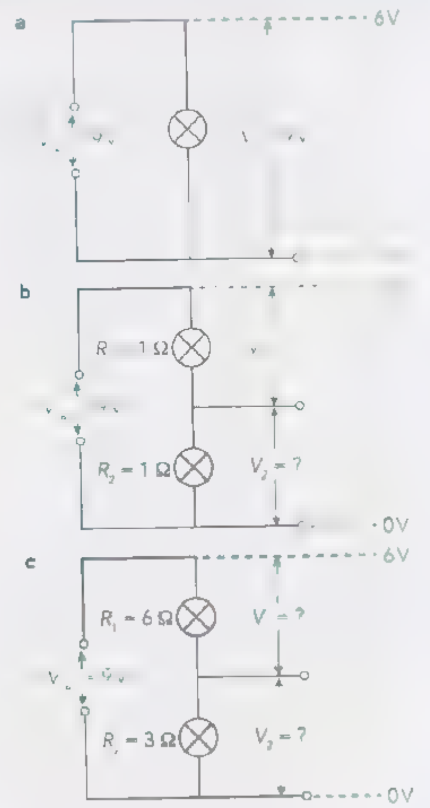


Figure 19.16: Potential divider circuits.

The circuit in Figure 19.16b has two lamps in series with a 9 V cell. Imagine that the resistance of both lamps is 1 Ω. We can calculate the current through this series circuit using the equation $R = \frac{V}{I}$, which is the equation we used to define resistance.

$$I = \frac{V}{R} = \frac{9\ \text{V}}{2\ \Omega} = 4.5\ \text{A}$$

This allows us to work out the voltage across each lamp using $V = IR$:

$V_1 = 4.5\ \text{A} \times 1\ \Omega = 4.5\ \text{V}$

$V_2 = 4.5\ \text{A} \times 1\ \Omega = 4.5\ \text{V}$

Notice that these voltages add up to the e.m.f. of the cell:

$V_{cell} = V_1 + V_2 = 4.5\ \text{V} + 4.5\ \text{V} = 9\ \text{V}$

Now imagine that lamp 1 has a resistance of $R_1 = 6\,\Omega$ and lamp 2 has a resistance of $R_2 = 3\,\Omega$ (as in Figure 19.16c). The combined resistance is $R = R_1 + R_2 = 6\,\Omega + 3\,\Omega = 9\,\Omega$

This time the current through the series circuit is

$$I = \frac{V}{R} = \frac{9\,V}{9\,\Omega} = 1.0\,A$$

This time the voltage across each lamp is:

$V_1 = 1.0\,A \times 6\,\Omega = 6.0\,V$

$V_2 = 1.0\,A \times 3\,\Omega = 3.0\,V$

Again, the p.d. across each lamp adds up to the e.m.f. of the cell. However, this time the p.d. across lamp 1 is twice as high as the p.d. across lamp 2, which is exactly the same ratio as their resistances:

$$\frac{R_1}{R_2} = \frac{V_1}{V_2}$$

KEY EQUATION

Resistance for two resistors used as a potential divider:

$$\frac{R_1}{R_2} = \frac{V_1}{V_2}$$

This seems to makes sense. The bigger the resistance of the lamp, the bigger the work done per unit charge, or voltage, required to push the charge through it.

WORKED EXAMPLE

A potential divider circuit is required to produce an output voltage of 8 V across a resistor, R_1, of 600 Ω. The supply voltage is 12 V. What is the required value of the series resistor, R_2?

Step 1: Sketch a circuit diagram and mark on the information from the question (Figure 19.17). Remember to add in the voltage across R_2 (the sum of the voltages across resistors in a series circuit must add up to the cell voltage, so, 12 V − 8 V = 4 V).

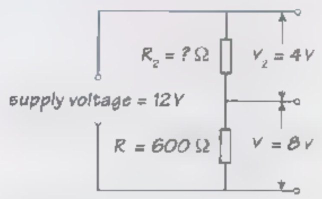


Figure 19.17: Sketch diagram.

CONTINUED

Step 2: Write down the potential divider equation applied to this problem.

$$\frac{R_1}{R_2} = \frac{V_1}{V_2}$$

Step 3: Substitute values from the question

$$\frac{600\,\Omega}{R_2} = \frac{8\,V}{4\,V} = 2$$

Step 4: Rearrange and solve for R_2

$$R_2 = \frac{600}{2} = 300\,\Omega$$

Answer

The series resistor, R_2, needs a value of 300 Ω

Question

12 a Work out V_1 and V_{in} in Figure 19.18a

b Work out V_1 and R_1 in Figure 19.18b

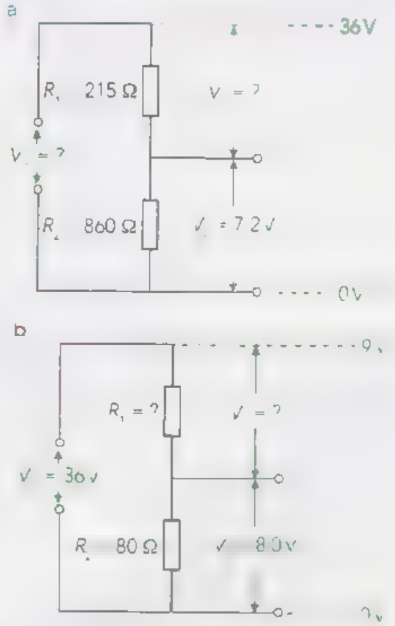


Figure 19.18

Current and resistance in parallel circuits

In the same way that energy is conserved (Chapter 6), electric charge is also conserved. Electrons in an electric circuit cannot appear from nowhere or disappear. Because charge is conserved, the charge arriving at any junction in a circuit must equal the charge (and therefore the current) leaving the same junction. This means that the total current ($I = Q/t$) coming into a junction must equal the total current (charge/time) leaving the same junction. Imagine cars arriving at a junction in the road: the number of cars leaving the junction must equal the number of cars that arrived. If that were not the case, the cars and their passengers would need to appear from nowhere or disappear, which would be quite alarming.

Therefore, we know that current divides up to pass through the branches of a parallel circuit. Adding up the currents through the two separate resistors gives the current flowing out of the power supply. The current from the supply is the sum of the currents flowing through the resistors.

$$I = I_1 + I_2$$

Because the resistors are connected side by side, each feels the full push of the supply.

To calculate the effective resistance R for two resistors in parallel, we use this equation:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

There are two ways to calculate this type of sum: either use a calculator, or add up the fractions by finding their lowest common denominator. Worked Example 19.3 shows how to use this equation, and how to work out the sum by finding the lowest common denominator.

WORKED EXAMPLE 19.3

One 10 Ω resistor and a 30 Ω resistor are connected in parallel with a 12 V power supply. Calculate:

a the effective resistance of the two resistors

b the current through each resistor

c the current flowing from the power supply.

Step 1: Sketch a circuit diagram and mark on it all the quantities you know (Figure 19.19). Add arrows to show how the current flows, like this.

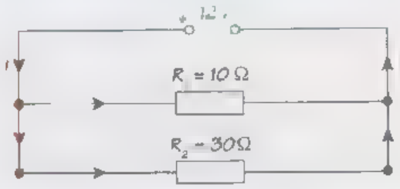


Figure 19.19: Sketch circuit.

Step 2: Calculate the effective resistance.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R} = \frac{1}{10\ \Omega} + \frac{1}{30\ \Omega}$$

$$\frac{1}{R} = \frac{4}{30\ \Omega}$$

$$R = 7.5\ \Omega$$

Step 3: Each resistor has a p.d. of 12 V across it. Now we can calculate the currents using the equation:

$$I = \frac{V}{R}$$

current I through 10 Ω resistor $= \frac{12\text{ V}}{10\ \Omega}$

$= 1.2\text{ A}$

current I through 30 Ω resistor $= \frac{12\text{ V}}{30\ \Omega}$

$= 0.4\text{ A}$

Notice that, as you might expect, the smaller (10 Ω) resistor has a bigger current flowing through it than the larger (30 Ω) resistor.

Step 4: The current, I, flowing from the supply is the sum of the currents flowing through the individual resistors.

$$I = 1.2\text{ A} + 0.4\text{ A} = 1.6\text{ A}$$

Note: we could have reached the same result using the effective resistance (7.5 Ω) of the circuit that we found in Step 2.

$$I = \frac{V}{R} = \frac{12\text{ V}}{7.5\ \Omega} = 1.6\text{ A}$$

This is a useful way to check that you have calculated the effective resistance correctly. Current divides in a parallel circuit, but the total amount must remain the same – electrons cannot just disappear.

CONTINUED

Answers

a The two resistors together have an effective resistance of 7.5 Ω.

b The 10 Ω resistor has a current of 1.2 A flowing through it. The 30 Ω resistor has a current of 0.4 A flowing through it

c There is a 1.6 A charge flowing from the power supply

Questions

13 Use the idea of resistors in series to explain why a long wire has more resistance than a short wire (of the same thickness and material)

14 Use the idea of resistors in parallel to explain why a thick wire has less resistance than a thin wire (of the same length and material)

15 A 15.0 Ω resistor is connected in series with a 30.0 Ω resistor and a 15.0 V power supply

- **a** Calculate the current flowing around the circuit
- **b** Which resistor will have the larger share of the p.d. across it?

16 One 6 Ω resistor and one 4 Ω resistor are connected in parallel with a 6 V power supply. Calculate

- **a** the effective resistance of the two resistors
- **b** the current through each resistor
- **c** the current flowing from the power supply.

Putting it all together

We now have enough knowledge to calculate the currents and voltages in more complex circuits. Electrical engineers often sketch equivalent circuits in order to solve them and we will do the same. For each resistor in Figure 19.20a, we are going to work out the current passing through it and the potential difference across it. Most of the steps can be done in a different order. It is the problem-solving strategy (or approach) that is important here. You may need to read through this example several times. Once you think you can follow the steps, cover up the working and see if you can solve it yourself. It may take you several attempts.

In Figure 19.20a, there is the same e.m.f. of 9 V across both branches of this circuit (that is, 9 V between A and B and as 9 V between C and E):

e.m.f. $= V_{AB} = V_{CE} = 9\,\text{V}$

The current through R_1:

$$I_{AB} = \frac{V_{AB}}{R_1} = \frac{9\,\text{V}}{6\,\Omega} = 1.5\,\text{A}$$

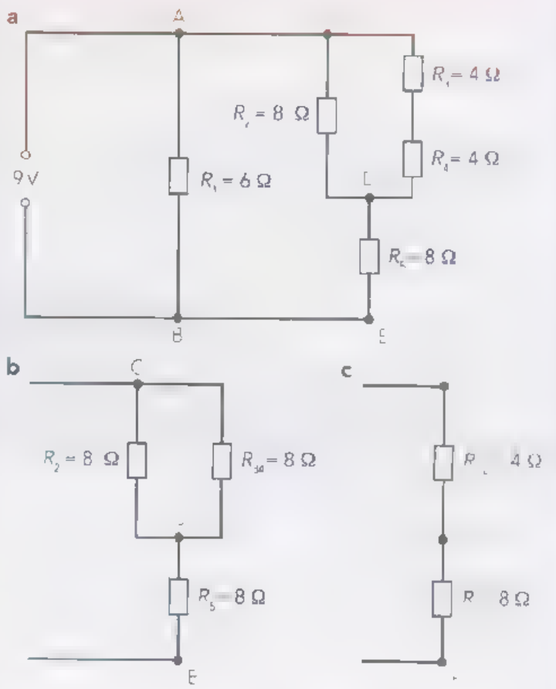


Figure 19.20: Circuit diagram examples.

The pair of series resistors R_3 and R_4 between C and D can be replaced with a single resistor of their combined resistance as shown in Figure 19.20b.

$$R_{34} = R_3 + R_4 = 4\,\Omega + 4\,\Omega = 8\,\Omega$$

There is now a pair of parallel resistors (R_2 and R_{34}) between C and D. They can be replaced with a single resistor (R_{CD}) as shown in Figure 19.20c.

$$\frac{1}{R_{CD}} = \frac{1}{R_2} + \frac{1}{R_{34}}$$

$$\frac{1}{R_{CD}} = \frac{1}{8\,\Omega} + \frac{1}{8\,\Omega}$$

$$\frac{1}{R_{CD}} = \frac{16}{64\,\Omega}$$

$$R_{CD} = 4\,\Omega$$

The combined resistance of the series resistors between C and E (Figure 19.20c) is:

$R_{CE} = R_{CD} + R_5 = 4\,\Omega + 8\,\Omega = 12\,\Omega$

The current between C and E is

$I = \frac{V}{R} = \frac{9\text{ V}}{12\,\Omega} = 0.75\text{ A}$

The p.d. across R_5

$V_5 = I_{CE}R_5 = 0.75\text{ A} \times 8\,\Omega = 6\text{ V}$

The p.d. across R_{CD}:

$V_{CD} = I_{CE}R_{CD} = 0.75\text{ A} \times 4\,\Omega = 3\text{ V}$

These potential differences add up to the e.m.f. of the source, as expected.

The current entering junction A (Figure 19.20a) must equal the current leaving the junction:

$I_{source} = I_{AB} + I_{CE} = 1.5\text{ A} + 0.75\text{ A} = 2.25\text{ A}.$

If you look at Figure 19.20b, you will see that there are two paths between C and D. Both paths have equal resistance and there is the same p.d. of 3 V across them; they must each carry half of the total current between C and D. This can be confirmed by working out the current in either branch between C and D

$I_{CD} = \frac{V}{R} = \frac{V}{R} = \frac{3\text{ V}}{8\,\Omega} = 0.375\text{ A}$

At D, the 0.375 A that has come down the left-hand branch joins with the 0.375 A that has come down the right-hand branch so that 0.75 A passes between D and E.

Now that we have the current through the pair of series resistors between C and D (R_3 and R_4) we can work out the p.d. dropped across each. Their resistance values are the same so they should each have a half share of the drop in p.d. between C and D (that is, 1.5 V across each of them). We can confirm this.

$V = I_{CD} \times R_3 = I_{CD} \times R_4 = 0.375\text{ A} \times 4\,\Omega = 1.5\text{ V}$

All the current and voltage values are summarised in Figure 19.21 and Table 19.1.

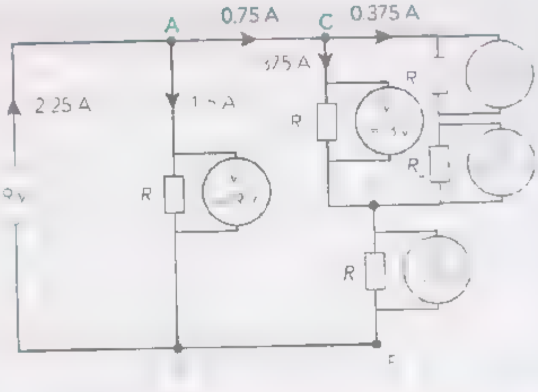


Figure 19.21

[illegible]	Source	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
Current / A	2.25	[illegible]	[illegible]

[illegible]	3	4	[illegible]
V	1.5	[illegible]	[illegible]
[illegible]	0.375	[illegible]	[illegible]

Table 19.1

Question

17 Work out the current through, and the voltage across, each lamp in the circuit (Figure 19.22). Summarise your results in a table like Table 19.1.

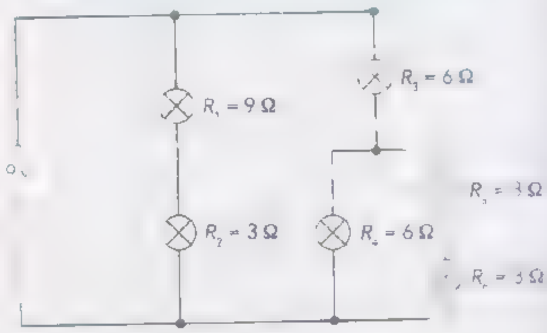


Figure 19.22

ACTIVITY 19.1

Series and parallel combinations of resistors

Task 1: Thinking about resistor combinations

Your teacher will give you some time to write down answers to the following questions:

- What is used to measure current and how is it included in circuit? Draw a sketch if it helps.
- What is used to measure voltage and how is it included in circuit? Draw a sketch if it helps.
- How can the resistance of an electrical component (such as a lamp) be measured?
- How can we calculate the total resistance for resistors in series?
- How can we calculate the effective resistance for two resistors in parallel?
- How is it possible to make more than one cell into a battery and does it matter which way round the cells are?

The two circuits, which are described below, use two lamps, a 3.0 V battery, and a switch. Assume that each lamp has a resistance of 5 Ω. Use this information to work out the missing values. Show your working and then write your answers onto a copy of Tables 19.2 and 19.3. Leave the shaded boxes blank.

Part 1: Series circuit

Use a pencil and a ruler to draw a neat series circuit with two lamps in series with a 3.0 V battery and a switch.

	Calculated current / A	Calculated voltage / V	Resistance / Ω
Battery		3.0	
Lamp 1			
Lamp 2			
Circuit			

Table 19.2

Part 2: Parallel circuit

Use a pencil and a ruler to draw a neat circuit using the same components you used for the series circuit with the lamps in parallel. Make it clear where you think the switch should be placed.

	Calculated current / A	Calculated voltage / V	Resistance / Ω
Battery		3.0	
Lamp 1			
Lamp 2			
Circuit			

Table 19.3

Your teacher will decide how you will check your answers and help resolve any misunderstandings.

CONTINUED

Part 3: Design your own

1 Design a slightly more complicated circuit (for example, two parallel lamps in series with a third lamp)

2 Predict the voltages and currents for all three lamps and the battery.

3 Write a question based on your circuit to test another student or pair of students.

Task 2: Building resistor combinations (optional)

If you have the time and equipment you may get the chance to build the circuits you have drawn in Task 1. Alternatively, you could build virtual circuits in an online simulation. If you are building physical circuits you will need:

- two 2.5 V lamps in holders
- at least two 1.5 V D cells in cell holders
- at least nine electrical leads
- voltmeter
- ammeter
- switch.

If you are building physical circuits you need to be aware of the following things.

The actual value of a component will be different from the value printed on its case. When using your circuits ensure that the switch is closed (pressed) only when taking measurements, otherwise the cells will drain quickly and the e.m.f. will change. The resistance of different lamps will also vary so the p.d. across them will not be the same.

The 2.5 V lamps need a p.d. of at least 2.0 V to light up. However, your circuits should still work (giving sensible ammeter and voltmeter readings) when the lamps do not light up.

If you use a copy of the tables (Tables 19.4 and 19.5) to record your results, leave the shaded boxes blank. The number at the top left hand corner of each cell refers to the step number. This is to make it easier for you to find where you should be writing in your numbers. Do your working in your exercise book.

Ignore (do not record) any negative signs on the voltmeter or ammeter. A negative sign tells you that the meter is connected the wrong way round (the current is passing in the wrong direction) but this does not affect the value.

Part 1: Series circuit

1 Use a pencil and a ruler to draw a neat series circuit with two 2.5 V lamps in series with a 3.0 V battery, a switch and an ammeter.

2 Build the circuit you have already drawn. Label the lamps as 'lamp 1' and 'lamp 2' and keep track of them.

3 By moving the ammeter, measure the current next to lamp 1, lamp 2 and the battery. Record your values in a table like Table 19.4

	Current / A		Voltage / V		Resistance / Ω	
	predicted	measured	predicted	measured	predicted	calculated
battery		13		4		
lamp 1		13		14		17
lamp 2		13	15	16		17
circuit						18

Table 19.4

4 Measure the e.m.f. across the battery and the p.d. across lamp 1 and record your values.

CONTINUED

5 Using your values from step 4, predict the p.d. across lamp 2 and record your prediction.

6 Measure the p.d. across lamp 2 and record your value.

7 Work out the resistance for each lamp by dividing the p.d. across it by the current passing through it by using $R = \frac{V}{I}$. Record your values.

8 Work out the total resistance of the two resistors in series. Use the total resistance of the series circuit and the battery e.m.f. to work out what the current should be and compare this to the value you actually measured (in part 1, step 3).

Part 2: Parallel circuit

1 Use a pencil and a ruler to draw a neat parallel circuit using the same components you have already used with the series circuit.

2 Build the circuit you have just drawn.

3 Use the e.m.f. of the battery to predict the voltage across the battery and each lamp. Record your predictions in a table like Table 19.5.

	Current / A		Voltage / V		Resistance / Ω	
	predicted	measured	predicted	measured	predicted	calculated
battery	2.7	2.8	2.3	2.4		
lamp 1	2.5	2.6	2.3	2.4		2.9
lamp 2	2.5	2.6	2.3	2.4		2.9
circuit						2.10

Table 19.5

4 Measure and record the e.m.f. across the battery and the p.d. across each lamp.

5 Use the resistance values you have already calculated (from part 1, step 7) to predict the current through each lamp ($I = \frac{V}{R}$).

6 Measure and record the current through each lamp.

7 Use the measured currents through the two lamps to predict the current through the battery.

8 Measure the current through the battery and compare this to the value you predicted in step 7.

9 Use the voltage and current data you have collected for the parallel circuit to calculate the resistance of each lamp and record your values.

10 Calculate the effective resistance of the circuit and record your value.

11 Use the battery e.m.f. and the effective resistance of the parallel circuit to predict the current through the battery. Compare it to your measurement (in part 2, step 8).

Part 3: Design your own

Now that you have some experience, look back at the circuit you designed yourself (Task 1, part 3). Use the values you have found for the battery e.m.f. and the resistance values of lamps to work out the current and voltage values throughout your circuit. Now build the circuit and check if you were correct.

CONTINUED

- Did the current change as it flowed around the series circuit?
- What is the relationship between the p.d. across the lamps and the e.m.f of the battery in the series circuit?
- What is the relationship between the p.d. across the lamps and the e.m.f. of the battery in a parallel circuit?
- What is the relationship between the current through the lamps and the current through the battery in a parallel circuit?
- Are the resistance values for the lamps in the two circuits different? If they are, can you suggest why?
- Show algebraically that for two resistors in parallel, the effective resistance is the product of their values divided by the sum of their values $R = \frac{R_1 R_2}{R_1 + R_2}$

PEER ASSESSMENT

Look at the circuit diagrams drawn by your neighbour and look at how they built the circuits based on their diagrams. Give your neighbour feedback on how they drew their circuits. The circuits should have been drawn clearly using the correct symbols, with a pencil and a ruler. If your neighbour had difficulty drawing or building the circuits can you give them some suggestions that might make it easier for them?

REFLECTION

This activity involved drawing circuits from a description and then building the circuit.

Rate how easy you found both these steps on a scale from 1 (very easy) to 5 (very hard)

If you found either or both steps difficult, what would make them easier?

ACTIVITY 19.2

How much do I know about circuits?

Spend a couple of minutes labelling a copy of the circuit diagrams in Figure 19.23 with as much information as you know, including arrows to show the direction of the current. Assume each lamp has a different resistance. Explain what is happening at different points of the circuit and include the following words: current, potential difference, junction.

CONTINUED

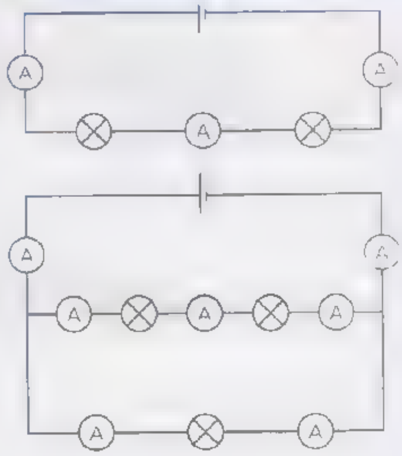


Figure 19.23

Make a table like Table 19.6 and fill it in to summarise the rules for current and voltage in series and parallel circuits.

	Current	Voltage
series		
parallel		

Table 19.6

19.3 Electrical safety

Mains electricity is hazardous, because of the large voltages involved. If you come into contact with a bare wire at 230 V, you could get a fatal electric shock. Here, we will look at some aspects of the design of electrical systems and see how they can be used safely

Electrical cables

The cables that carry electric current around a house are carefully chosen. Figure 19.24 shows some examples. For each, there is a maximum current that it is designed to carry. A 5 A cable (Figure 19.24a) is relatively thin. This might be used for a lighting circuit, since lights do not require much power, so the current flowing is relatively small. The wires in a 30 A cable (Figure 19.24c) are much thicker. This might be used for an electric cooker, which requires much bigger currents than a lighting circuit.

The wires in each cable are insulated from one another, and the whole cable has more protective insulation around the outside. If this insulation is damaged, there is a chance that the user will touch the bare wire and get an electric shock.

Figure 19.24: Cables of different thicknesses are chosen according to the maximum current that they are likely to have flowing through them **a:** 5 A **b:** 15 A. **c:** 30 A. Each cable has live, neutral and earth wires, which are colour coded In these cables, the earth wire does not have its own insulation

Another hazard can arise if an excessive current flows in the wires. They will overheat and the insulation may melt, causing it to emit poisonous fumes or even catch fire. Thus it is vital to avoid using appliances that draw too much current from the supply. Fuses help to prevent this from happening.

When using electricity, it is important to avoid damp or wet conditions. Recall that water is an electrical conductor (see Section 18.1) So, for example, if your hands are wet when you touch an electrical appliance, the water may provide a conductive path for current to flow from a live wire through you to earth. This could prove fatal.

Multi-plug adapters

The number of electrical appliances people use in their homes is increasing The safest option is to have more wall sockets fitted. The alternative is to use multi-plug adaptors that allow us to plug more than one device into the same wall socket. Multi-plug adaptors come in two main varieties. The safer option is to use a multi-way bar extension, which comes as a bank of sockets on the end of an extension lead that can be plugged into a wall socket, as shown in Figure 19.25 These are generally fitted with a fuse to match the wall socket (13 A in the UK).

Figure 19.25: A multi-way bar extension with four available sockets and white electrical cable (on the right). There is a block adapter with three sockets plugged into the left hand end of the extension Plugging multi-plug adapters together should be avoided

Be wary of block adaptors, which are plugged directly into a wall socket. They usually have a cubic shape and two or more sockets (see the left-hand side of Figure 19.25). These are less likely to contain a fuse so there is an increased danger that a current will exceed the rating of the wall socket. Overloading the socket in this way increases the chance that it, and the plug, will heat up and catch fire.

It is important not to exceed the current rating of any part of the system. Imagine there are four devices, each drawing a current of 3 A. This would not overload a wall socket so they could be plugged into the same wall socket via a fused multi-plug adaptor. However, if an extension is rated at 10 A, no more than three of its sockets should be used, even if more sockets are available. Avoid using a block adapter that does not have a fuse. Never join multi-plug adapters together. For example, do not plug a block adapter into an extension as shown in Figure 19.25

Questions

18 Name the two main types of multi-plug adapters.

19 What is often missing from a block adapter that makes it more dangerous to use than a multi-plug adapter?

20 Why is it important not to overload a wall socket or any multi-plug adapter plugged into it?

Fuses

Fuses are included in circuits to stop excessive currents from flowing. This protects the circuit and the cabling for a domestic appliance. If the current gets too high, cables can burn out and fires can start. A **fuse** contains a thin section of wire, designed to melt and break if the current gets above a certain value. Usually, fuses are contained in cartridges, which makes it easy to replace them, but some fuses use fuse wire, as shown in Figure 19.26. The thicker the wire used for the fuse, the higher the current that is needed to make it melt (or blow). A fuse represents a weak link in the electricity supply chain. Replacing a fuse is preferable to having to rewire a whole house.

fuse: a device that breaks the circuit if the current exceeds a certain value; it is a piece of metal wire that melts when too much current flows through it

Figure 19.26. Cartridge fuses and fuse wire. The thicker the wire, the higher the current that causes it to melt.

It is important to choose a fuse of the correct value in order to protect an appliance. The current rating of the fuse should be just above the value of the current that flows when the appliance is operating normally (see Worked Example 19.4).

A 2 kW heater works on a 230 V mains supply. The current flowing through it in normal use is 8.7 A.

What current rating would a suitable fuse have?

- 3 A
- 13 A
- 30 A.

Step 1: The 3 A fuse has a current rating that is too low, and it would melt as soon as the heater was switched on.

Step 2: The 30 A fuse would not melt, but it is unsuitable because it would allow an excessive current (say, 20 A) to flow, which could cause the heater to overheat.

Step 3: The 13 A fuse is the correct choice, because it has the lowest rating above the normal operating current.

Answer

13 A

Trip switch

A **trip switch** can replace a fuse. The switch trips and breaks the circuit when the current flowing through the trip switch exceeds a certain value. Some modern house wiring systems use trip switches instead of fuses in the fuse box (Figure 19.27). You have probably come across trip switches on laboratory power supplies. If too much current starts to flow, the supply itself might overheat and be damaged. The trip switch jumps out, and you may have to wait a short while before you can reset it.

trip switch: safety device that includes a switch that opens (trips) when a current exceeds a certain value

Figure 19.27: This is where the mains electricity supply enters a house. On the left is the meter. The white box contains a trip switch for each circuit in the house, together with a residual-current device, which protects the users of any circuit.

Questions

21 In normal use, a current of 3.5 A flows through a hair dryer. Choose a suitable fuse from the following: 3 A, 5 A, 13 A, 30 A. Explain your choice.

22 **a** Why are fuses fitted in the fuse box of a domestic electricity supply?

b What device could be used in place of fuses?

23 What hazards can arise when the current flowing in an electrical wire is too high?

Using an earth wire or double insulation

We have already seen why the insulation on wires is important – to prevent fires or an electric shock. This is because there is a chance that current will flow between two bare wires (a short circuit), or from one bare wire and any piece of metal it comes into contact with. This is why the metal case of an electrical appliance is **earthed** by connecting it to the earth wire. The earth wire provides a low resistance electrical path to ground and reduces the chances of a fatal electric shock.

A mains circuit consists of a live (or line) wire, a neutral wire and an earth wire. These are carried around buildings as part of the ring mains and we can plug into it via wall sockets. If you have ever seen inside an electrical plug or an electrical cable, you will have noticed different coloured wires. Actually, this is the plastic insulation, and it is colour coded so that people can wire up plugs and appliances safely. The live wire (coloured brown in the UK) carries the electrical current from the wall socket to the electrical appliance (such as a television) and the neutral wire (blue in the UK) carries the current back to the socket. There is usually also an earth wire (yellow and green stripes).

Figure 19.28a shows the wiring when there is no fault. Notice that the earth wire is connected between the casing of the appliance and the earth pin of the plug. This is a schematic diagram (to show you what is happening). The coloured wires are all inside the electrical cable (see Figure 19.24) and the connection to the metal case is actually made from inside the appliance.

Imagine that there is now a fault (Figure 19.28b) and the live wire touches the metal case. The case will now be at the mains voltage (230 V in the UK). Anyone touching the casing could receive a fatal shock. However, the earth wire provides a low resistance path to ground. You can trace the path of the current with your finger. It passes through the live pin at the bottom right of the plug, along the live wire (through the fuse) to the metal casing and then along the earth wire. Because the resistance of this path is low and the voltage is high, a high current will pass through the fuse, which will almost instantly melt, stopping any current flowing to the appliance.

A switch on the electrical appliance must be connected to the live wire. If it was connected to either the neutral wire or the earth wire, a current could still pass into the appliance even if the switch was open (off) and this could lead to a fire or to somebody being electrocuted if they touched a faulty appliance. Imagine that there was a fault and a live wire touched the metal casing. Nothing would happen and no current would flow as long as the circuit was incomplete (an open circuit). If the casing touched something that could conduct the current to ground, then a fire might start. The current could pass through someone touching the casing, giving them an electric shock. Think about what would happen if the fuse was connected to the neutral or earth wire.

earthed: when the case of an electrical appliance is connected to the earth wire of a three-pin plug; the earth wire is electrically connected to the ground to prevent current passing through anyone touching a faulty appliance

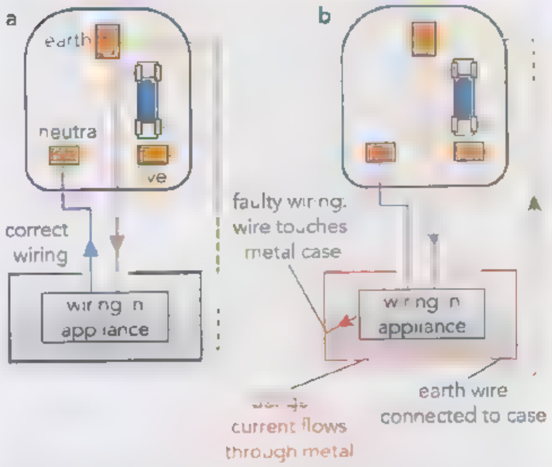


Figure 19.28a: How the current flows from the live pin of the p ug a ong the live wire (brown) to the appl ance and back to the plug and socket along the neutral wire (blue). **b:** When there is a fault and a bare w re in the appliance touches the metal casing, the current flows through the earth wire (green and yellow stripes) instead of the neutral wire, and the fuse melts because a large current flows along this low res stance path.

Electrical appliances that are **double insulated** do not need an earth connection (only two wires are wired into the three-pin plug). Even if there are metal parts on the outer casing, the electrical circuit for the appliance is inside a case underneath, which is made from electrically insulating material (for example, plastic) so that an electric current cannot pass through it. There is no way that a live conductor could touch the outer case. This means that there is no way that somebody touching the outer case could be electrocuted. When the symbol shown in Figure 19.29 is stuck to the casing of an electrical appliance, then it is double insulated.

Figure 19.29: The symbol for doub e insu ation. If you see this stuck to the casing of electrical appliance then it will not need an earth wire.

double insulated: when the electric circuit for an electrical appliance is placed inside a case made from an electrical insu ator so that it is impossible for a ive wire to touch the outer cas ng

Questions

24 Explain how an earth wire makes an electrical device safe.

25 Why must a switch be connected to the live wire and not the earth wire or neutral wire?

26 Why should a fuse be connected to the live wire and not the earth wire or neutral wire?

27 Explain how a fuse works.

28 What is double insulation?

ACTIVITY 19.2

Challenging misconceptions using refutation texts

If what you think about an idea is incorrect then you have a misconception. A refutation text is when you state the misconception and then wr te down the correct idea.

Most people talk about the cell or battery in mobile phones running out of charge believing that, when we charge our phones, we are transferring charge (electrons) into it. However, this cannot be true or we might get an electric shock when we pick up a ful y charged phone! The cell or battery s more l.ke a pump, pushing the charges round the circu t. Here is an example of a refutation text about charging a phone.

'Some peop e think that electrons are passing into the battery when we charge it up, but we are transferring energy to its battery.'

Complete each statement to refute the incorrect dea:

1 Some people think that current gets used up by a lamp, but

2 Some people think that all the amps n a series circuit will be the same br ghtness, but .

3 Some people believe that the current through both lamps in a parallel circuit will be the same, but

The shocking truth about electrical safety

Read the following passage.

> **Summary of government research into recent house fires and hospital admissions**
>
> *The frequency of house fires and people experiencing electric shocks in the home (some fatal) has increased. Our research suggests that people are confused about electrical safety. For example, more than two-thirds of people surveyed believe that an appliance is safe no matter where in the circuit the fuse is placed. Most of those questioned think it is safe for the fuse or switch to be on the neutral wire (on the return side of the circuit). More than 80% of people think it is safe to fill all the available sockets on a multi-plug adapter with an appliance as long as each appliance has a fuse. A public education campaign should be launched as a matter of urgency*

Option 1: A government leaflet

Design a government information leaflet about electrical safety. Give it visual impact. Where possible, use labelled illustrations instead of text. Do not exceed 100 words. Highlight the dangers of using:

- household electrical appliances in damp conditions or with damaged insulation
- multi-plug adapters (especially those that do not include a fuse) and of joining multi-plug adapters together.

Emphasise the importance of using the correct fuse rating and of placing fuses and switches in the correct place in a circuit.

Option 2: A narrated animation

A narrated animation is a moving picture with a voiceover. Develop a narrated animation to explain why fuses and switches should be on the live wire (the supply side) of an appliance. Show the path taken by the current when the fuse (and/or switch) is in the wrong place and a fault occurs (for example the live wire touches the metal case). Be careful how you show the current passing through somebody to avoid upsetting viewers (by using humour, for example). Then show the path when the fuse (and/or switch) is in the correct place. If you do not have access to animation software you could photograph a series of drawings to get the same effect

Option 3: Explaining by storytelling

Use creative writing (a short story) to explain the science. For example, pretend that you are an evil electron on the hunt for unsafe electrical circuits and describe how you can spot them from the inside. Or you could be an electron with a sense of adventure, looking to break free of life moving along a wire. Use one of these ideas if you cannot think of another one. Whatever creative device you choose, you need to avoid getting carried away with the story, though it does need a clear plot. The story is simply there to engage the reader; your mission is to get across the very important safety message.

SUMMARY

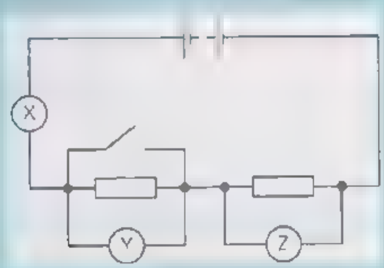
A resistor can control the amount of current flowing around a circuit.
A variable resistor can alter the current flowing in a circuit.
A light-dependent resistor (LDR) is a device whose resistance decreases when light shines on it.
A thermistor is a device whose resistance decreases with increasing temperature
A relay is a switch controlled by an electromagnet
A diode is a component that allows conventional current to flow only in the direction of the arrow
A light-emitting diode (LED) is a diode that gives out light when current flows through it

CONTINUED

Resistors in series are connected end to end
For resistors in series, the total resistance is the equal to the sum of the resistors
The current is the same at all points around a series circuit.
The voltage of the source is shared between resistors in a series circuit
A potential divider circuit uses a pair of resistors to obtain a smaller p.d. than provided by the source
For resistors arranged in parallel, the effective resistance is less than the value of the smallest resistor.
To calculate the effective resistance, R, for two resistors in parallel, we use the equation $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$
The current from the source divides to pass through parallel resistors.
The current from the supply is the sum of the currents flowing through parallel resistors: $I = I_1 + I_2 + I_3$.
Lights in a house are arranged in parallel so that each has the supply voltage across it and can be controlled by its own switch.
The metal case of an electrical appliance is earthed by connecting it to the earth wire to prevent current passing through anyone touching a faulty appliance.
Excessive current through a wire can melt insulation, causing it to emit poisonous fumes or catch fire.
Using multi-plug adapters (multi-way bar extensions and block adapters) increases the risk of overloading plugs and sockets.
A fuse contains a thin section of wire, designed to melt and break the circuit if the current gets above a certain value.
A circuit breaker is a safety device that automatically switches off a circuit when the current becomes too high
A trip switch is a safety device that includes a switch that opens (trips) when a current exceeds a certain value.

EXAM-STYLE QUESTIONS

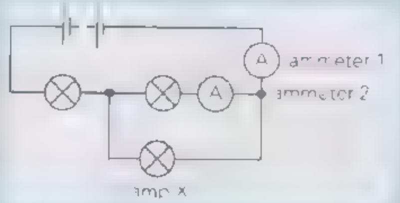
1 The circuit diagram shows three meters labelled X, Y and Z. You can work out whether each of them is a voltmeter or ammeter from the way in which they are connected. The switch is open.



When the switch is closed, the readings on the meters change.
Choose the correct combination from the options available. **[1]**

	X	Y	Z
A	increases	decreases	increases
B	decreases	decreases	increases
C	increases	increases	decreases
D	decreases	increases	decreases

2 The circuit shows three lamps and two ammeters in a circuit.



When lamp X stops working (the filament breaks), the readings on the meters change. Choose the correct combination from the options available. **[1]**

	Reading on ammeter 1	Reading on ammeter 2	Total resistance of circuit
A	decreases	increases	decreases
B	decreases	increases	increases
C	increases	decreases	decreases
D	increases	increases	increases

3 Two resistors R_1 and R_2 are connected in series. Resistor R_1 has double the resistance of resistor R_2.

Four possible statements about this circuit are:

1 The voltage across R_1 is twice that across R_2

2 The voltage across R_2 is twice that across R_1

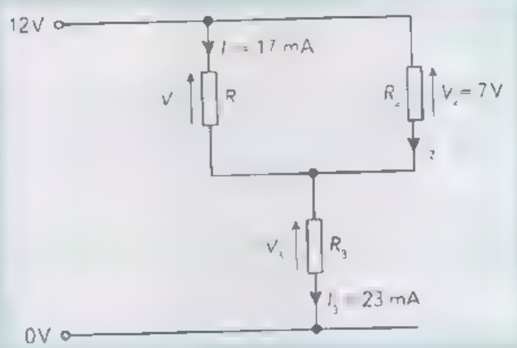
3 The current is the same in both resistors.

4 The current in R_1 is twice the current in R_2.

Which pair of statements is correct? **[1]**

A 1 and 4 **B** 2 and 3 **C** 1 and 3 **D** 2 and 4

4 Study the following circuit containing three resistors.



a Calculate the value of V_1. [1]

b Calculate the value of V_3. [1]

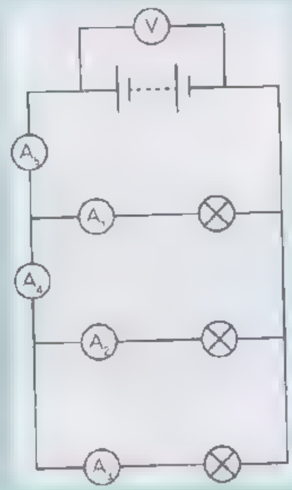
c Calculate the value of I_2. [1]

d The resistor network could be replaced with a single resistor. Calculate its resistance value. [2]

[Total: 5]

calculate work out from given facts, figures or information

5 A circuit was set up as shown in the diagram.



CONTINUED

a The table gives the current through three of the ammeters. Copy and complete the table to show the current through the other two ammeters. [2]

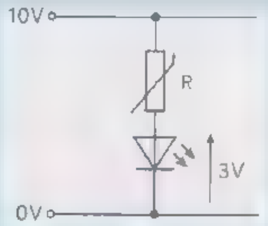
Ammeter	Reading on ammeter / A
A_1	0.7
A_2	1.2
A_3	0.7
A_4	
A_5	

b The filament in the middle lamp breaks. Copy and complete the table to show the readings on the ammeters after this took place. [3]

Ammeter	Reading on ammeter / A
A_1	0.7
A_2	0.0
A_3	
A_4	
A_5	

[Total: 5]

The circuit diagram shows part of a sensing circuit. The LED is to be used as a temperature warning indicator when the temperature exceeds a certain value. The LED requires a current of at least 14 mA in order to switch on (that is, emit light).



a Name the component labelled R in the circuit diagram. [1]

b State the minimum current through component R when the LED is emitting light. [1]

c Calculate the voltage across the component R when the LED is lit. [1]

d Calculate the resistance of R to ensure that a current of 14 mA passes through it. [1]

e The resistance of component R decreases as the temperature increases. Determine what happens to the size of the current through the LED as the temperature increases. [1]

[Total: 5]

COMMAND WORDS

state: express in clear terms

determine: establish an answer using the information available

7 Many circuits contain fuses. Figure 19.26 shows a cartridge fuse. A lamp is connected to the mains supply and takes a current of 6.2 A.

a State two reasons why is a fuse is included in the circuit. [1]

b Which of these fuses should be used with the lamp? [1]

A 3 A B 5 A C 7 A D 13 A

c Explain how a fuse works. [2]

d Name another device that does the same job as a fuse. [1]

e Explain why is it important to avoid touching a lamp or other electrical appliance with wet hands. [2]

f State what can be attached to the metal case of an electrical appliance to prevent an electric shock if the appliance is faulty. [1]

[Total: 8]

explain: set out purposes or reasons, make the relationships between things evident; provide why and/or how and support with relevant evidence

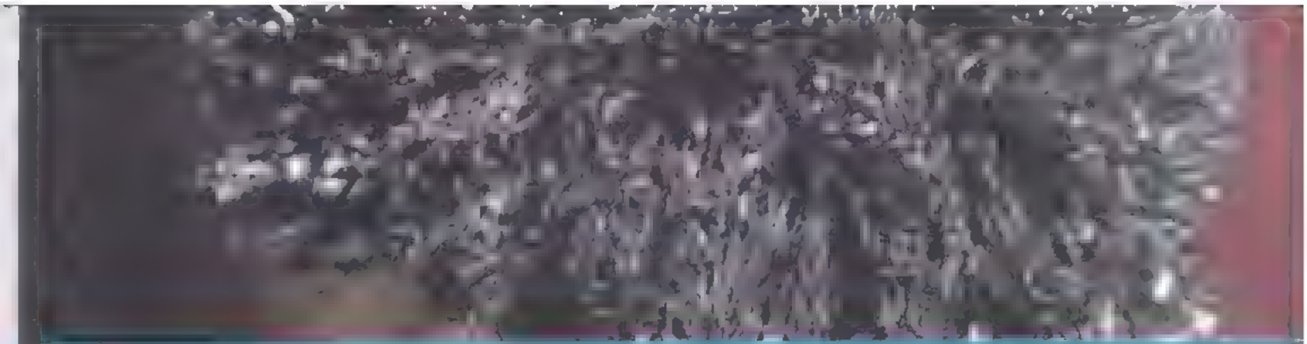
SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	Topic...	more work	there	to move on
Recall what LDRs and thermistors are	19			
Describe what a relay is and describe how it works in a switching circuit.	19.1			
Describe what diodes and LEDs do and how they work.	19.1			
Recall whether current varies around a series circuit.	19.2			
Calculate the combined resistance of two or more resistors in series.	19.2			
State the relative size of current through the source (for example, a cell or battery) and each branch of a parallel circuit.	19.2			
State how the combined resistance of two resistors in parallel compares to the resistance of either resistor by itself.	19.2			
State the advantages of connecting lamps in parallel in a lighting circuit.	19.2			
Recall and use the relationship between the sum of the p.d.s across the components in a series circuit and the p.d. across the source (for example, a cell).	19.2			

CONTINUED

[illegible]	[illegible]	Needs more work	Almost there	Confident to move on
Recall and use the relationship between the current from the source and the sum of the currents in the separate branches of a parallel circuit	19.2			
Calculate the effective resistance of two resistors in parallel.	19.2			
Describe the action of a potential divider	19.2			
State the hazards of using electrical appliances in damp conditions, when cables overheat or when insulation is damaged.	19.3			
State the hazards of using multi-plug adapters	19.3			
State what a fuse is used for and describe how it works.	19.3			
Choose appropriate fuse ratings and circuit breaker settings	19.3			
Explain the benefits of earthing the metal case of an electric appliance.	19.3			
State what a trip switch is and how it works.	19.3			



› Chapter 20

Electromagnetic forces

[illegible]

- investigate the magnetic fields around current-carrying conductors
- describe some practical uses of electromagnets
- observe the force on a current-carrying conductor in a magnetic field
- describe the principle of an electric motor and list ways of increasing its strength

› [illegible]

› [illegible]

GETTING STARTED

In Chapter 16 you studied magnetism. Chapters 17–19 covered electricity. As you can tell from the title, this chapter brings electricity and magnetism together. There are many links between the two, and also, important differences.

On a large sheet of paper, copy and complete the Venn diagram shown in Figure 21.1. In the overlapping section, write all the things which are similar. In the other sections, write down things which only apply to electricity or to magnetism. Two examples are given for you.

Electromagnetism was first described by a Danish scientist named Oersted in the early 19th century. Use the ideas you have recorded to discuss what might have lead Oersted to think there was a link between electricity and magnetism.

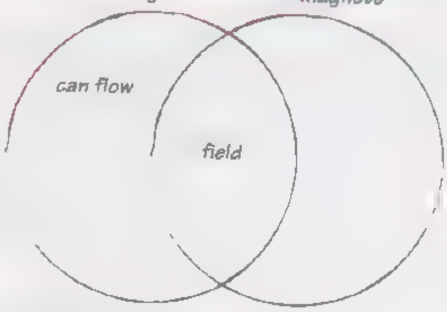


Figure 20.1: Venn diagram

THE MAGIC OF MOTORS

Figure 20.2: Small motors in prosthetic limbs allow a ... range of movement for people using them

... things in science seem magical. For example, ... fact that a plant can feed itself using sunlight ... zing. The electric motor is another example ... magic of science. As you will discover in this ... putting together an electric current and a ... field creates movement. This is the basis of ... motors

... motors have revolutionised our lives. It's ... to take them for granted, but anything you ... which involves movement, contains a motor. ...ng machines, hair dryers, electric vehicles, ... players and many more appliances which make our lives easier and better use motors. Just think for a moment about how different your life would be without motors.

Motors have many medical applications. They are widely used in prosthetic limbs, and can pump fluids such as blood during dialysis. Surgeons can remotely control motorised devices to make surgery less invasive.

Figure 20.2 shows a girl with a prosthetic arm eating her dinner. Many prosthetic limbs have small motors inside them, greatly increasing the capabilities of the artificial limb. Here, the motor allows the fingers to grip the French fries and apply the right amount of force to keep hold of them for her to then eat. Motors can be life changing and in this case, replaces the movement lost to an amputee.

Discussion questions

1 List all the applications of motors you can think of. Discuss how the job each application performs would have been done before motors were invented.

2 Discuss if you think there are any other scientific inventions or discoveries which have had as much impact as the electric motor.

20.1 The magnetic effect of a current

In Chapter 16, we saw that an electromagnet can be made by passing a current through a coil of wire (a solenoid). The flow of current results in a magnetic field around the solenoid. The field is similar to the field around a bar magnet (see Figure 16.8).

If you uncoil a solenoid, you will have a straight wire. With a current flowing through it, it will have a magnetic field around it as shown in Figure 20.3. The field lines are circles around the current.

Every electric current creates a magnetic field around it. An electromagnet uses this effect. Winding the wire into a coil is a way of concentrating the magnetic field.

The **right-hand grip rule** tells you the direction of the field lines. Imagine gripping the wire with your right hand so that your thumb points in the direction of the current. The curve of your fingers shows the shape and direction of the field lines.

We represent magnetic fields by drawing field lines. The arrows on the lines show the direction of the field at any point. A field line shows the direction of the force on a north magnetic pole placed in the field.

A solenoid is a length of wire wound to form a coil. It has a field pattern like that of a bar magnet, with field lines emerging from a north pole at one end of the coil and entering a south pole at the other (Figure 16.8).

Figure 20.3: Magnetic field around a wire

KEY WORDS

right-hand grip rule: a rule which gives the direction of field lines around a straight wire when a current flows through it

EXPERIMENTAL SKILLS 20.1

Investigating the magnetic effect of a current

Oersted's first experiment with electromagnetism involved just a simple circuit and a plotting compass. You will see what he observed and look at the fields around different shapes of wires.

Safety: The wire will become very hot when the current flows. Switch the power supply off as soon as you have made your observations. Avoid touching the wire.

Iron filings can scratch the cornea of your eye. Wear eye protection while using iron filings. If you get filings in your eye, tell your teacher immediately. Do not rub your eye as this will make it worse.

Getting started

In Chapter 16 you investigated the field around a bar magnet.

- What do the iron filings tell you about a magnetic field?
- What is the purpose of the plotting compasses?
- Sketch the magnetic field around a bar magnet.

CONTINUED

You will need

- power pack
- plotting compasses
- two pieces of stiff card, approximately 10 cm square, one with a hole through the centre, the other with two rows of holes (as shown in Figure 20.6)
- length of copper wire with the ends stripped
- clamp and stand
- iron filings.

Part 1: Oersted's experiment

1. Place a plotting compass on the table.
2. Place the wire over the compass as shown in Figure 20.4. The wire should be at right angles to the compass needle.
3. Switch on the power supply and watch what happens to the compass needle.
4. Investigate the effect of switching the connections to the power supply so the current is reversed.

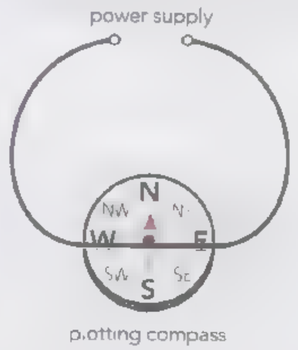


Figure 20.4

Part 2: Investigating the field around a straight wire carrying current

1. Pass the wire through the card and clamp the card so it is horizontal, as shown in Figure 20.5.

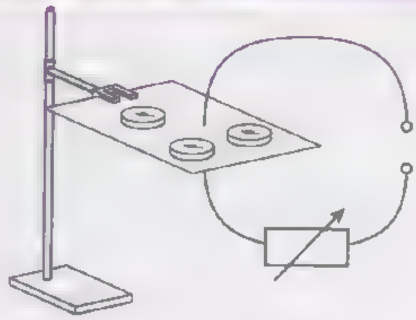


Figure 20.5

2. Place plotting compasses around the wire.
3. Sprinkle iron filings on to the card, around the wire.
4. Switch on the power supply and tap the card gently to allow the iron filings to move.
5. Observe the direction of the plotting compasses and then switch off the power supply.
6. Draw the pattern formed by the field lines. Mark the direction of the current and the field lines.

Part 3: Investigating the field around a solenoid

1. Thread the wire through the holes in the second card to create a coil of wire as shown in Figure 20.6.

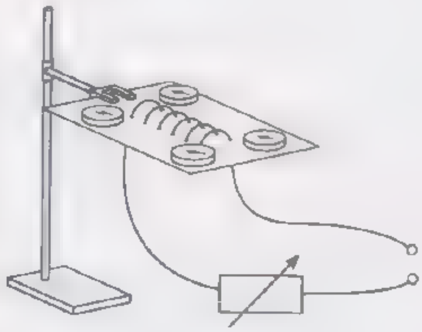


Figure 20.6

2. Repeat part 2, steps 2–6.

CONTINUED

Questions

1 Do your observations of the field around a straight wire agree with the right-hand grip rule?

2 In Chapter 16, we saw a method for determining the polarity of the field around a solenoid. This depends on the direction of current flow at each end of the coil.

Do your observations agree with this method?

Figure 20.7

3 A current flows downwards in a wire that passes vertically through a small hole in a table top. Will the magnetic field lines around it go clockwise or anticlockwise, as seen from above?

Comparing the strength and direction of magnetic fields

Current in a wire

Further from the wire, the circular field lines are further apart, showing that the field is weaker. If the current is greater, the field will be stronger and so the lines will be closer together.

The direction of the field lines is reversed when the current is reversed.

Current in a solenoid

The field lines are close together at the poles of the electromagnet. Further from the coil, the lines are further apart (illustrating a weaker field). Inside the coil the field lines run parallel to each other showing that the field is uniform (its strength is constant). Again, increasing the current gives a stronger field.

The polarity of the field is reduced when the current is reversed.

Questions

1 Copy and complete these sentences.

There is a magnetic field around a conductor when it carries ____

The field lines around a straight wire are ____

The direction of these field lines can be found using the ____ ____ ____ rule.

The field around a solenoid is the same as that around a ____ ____

2 What must be added to a solenoid to make it into an electromagnet?

Electromagnetism in action – the relay

A relay is a switch operated by an electromagnet. In Chapter 19, we saw how a relay can be used in an electric circuit. One type is shown in Figure 20.8, together with the circuit symbol.

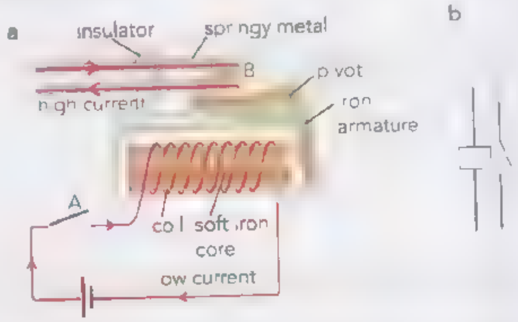


Figure 20.8a: A relay, capable of switching a circuit carrying hundreds of amps. **b:** The circuit symbol for a relay. The rectangle represents the electromagnet coil.

- When switch A is closed, a small current flows around the circuit through the coil of the electromagnet.
- The electromagnet attracts the iron armature. As the armature tips, it pushes the two contacts at B together, completing the second circuit.
- Notice that there is no electrical connection between the two circuits.

armature: the moving part of an electromagnetic device such as a relay or bell

A relay is used to make a small current switch a larger current on and off. For example, when a driver turns the ignition key to start a car, a small current flows to a relay in the engine compartment. This closes a switch to complete the circuit, which brings a high current to the starter motor from the battery. This means that the wires in the dashboard can be thin wires carrying a small current. This is safer, neater and cheaper than running thick wires carrying the large current needed by the starter motor all the way up to the dashboard. Figure 20.9 shows a relay being used in this way.

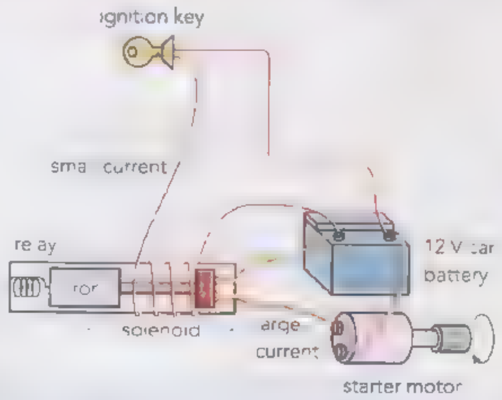


Figure 20.9: A relay is used to start a car engine.

Modelling a relay

It can be difficult to understand the way a relay works without seeing it in action.

Design a teaching aid to help you describe it to other students. This could be a video or storyboard showing the effect of switching on the small current circuit. Alternatively, you could create a working model by drawing the relay on card and having separate moving parts such as the secondary circuit connections and the armature. Whichever option you choose, you should write a voiceover script to describe and explain what is happening.

Present your work to another group of students.

The audience should give smiley, straight or sad face feedback on:

- how clear and well labelled the diagram or model is
- how well the video, series of pictures or movement of the model shows the way the primary circuit controls the secondary circuit
- the clarity of the explanation in the voiceover.

Feedback may also include any parts of the presentation which were particularly helpful, or suggestions for improvements to the presentation.

What aspect of this activity did you find most useful? Giving an explanation or listening to another student's explanation? If you were to continue with this activity, would you find the feedback you received useful?

Questions

4 a Figure 20.10 shows an electromagnetic relay used to switch on a motor.

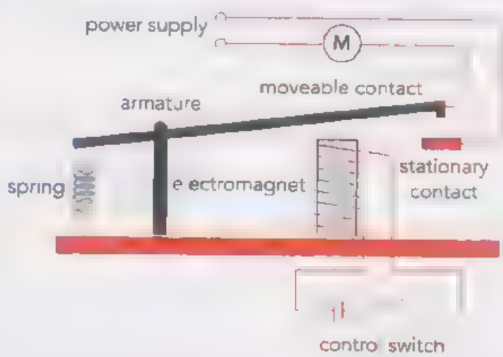


Figure 20.10: Relay used to switch on a motor

Write out these steps in the correct order to explain what happens when the control switch is closed.

- The contacts close together.
- Current flows through the electromagnetic coil

- Current flows in the motor circuit
- The electromagnet attracts the armature.
- The electromagnet is magnetised.

b Why is the armature made of iron?

c Why must soft iron be used?

5 Figure 20.11 shows an electromagnet in use in a signal for a model railway set.

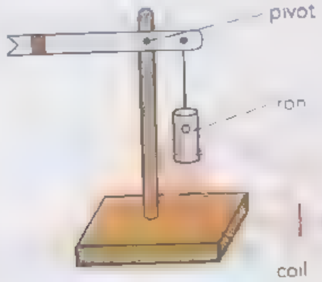


Figure 20.11: Electromagnet used as a signal.

Explain what happens when the switch is closed, and then when it is re-opened.

20.2 Force on a current-carrying conductor

The idea of an electric motor is this. There is a magnetic field around an electric current. This magnetic field can be attracted or repelled by another magnetic field to produce movement. This is called the motor effect.

motor effect: when current flows in a wire in a magnetic field which is not parallel to the current, a force is exerted on the wire

An electric motor has a coil with a current flowing around it (an electromagnet) in a magnetic field. It turns because the two magnetic fields interact with each other. However, it is not essential to have a coil to produce movement. The basic requirements are:

- a magnetic field
- a current flowing which cuts across the magnetic field lines.

Figure 20.12 shows a way to demonstrate this.

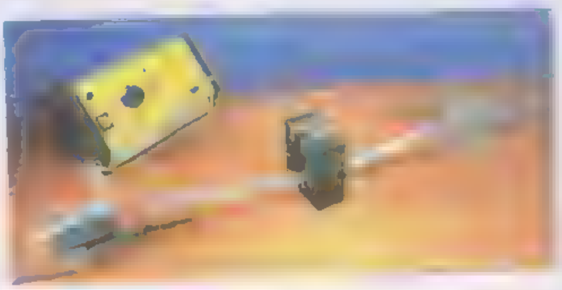


Figure 20.12: The motor effect. This can be summarised as current + magnetic field = movement.

When a current is passed through the aluminium foil it has a magnetic field around it. This interacts with the field of the strong, permanent magnet creating a force. The foil has been pushed downwards by this force.

The direction of the force can be reversed by:

- reversing the direction of the current
- reversing the direction of the field of the permanent magnet by turning it round.

EXPERIMENTAL SKILLS 20.2

The catapult field

Safety: The wires will get hot when current flows. Switch off the power supply as soon as you have observed movement and avoid touching the wires.

Getting started

This experiment works because two magnetic fields interact.

Sketch the magnetic field between two opposite poles and around a wire which is carrying current.

How could you reverse the direction of the field in each case?

You will need:

- power supply
- 2 magnadur magnets with a yoke
- 2 steel rods
- clamp
- copper wire.

CONTINUED

Method

1 Clamp two steel rods horizontally, parallel to one another.

2 Bend a length of copper wire (see Figure 20.13) to form a 'swing', which can hang between the steel rods

3 Attach the two magnets to the yoke, ensuring that opposite poles are facing each other. Place the magnets around the swing, as shown in Figure 20.13.

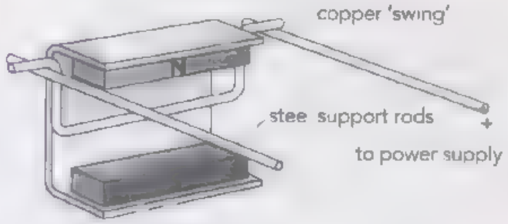


Figure 20.13: Set-up for investigation.

4 Connect up the ends of the steel rods to a low-voltage d.c. power supply The current should be able to flow along one rod, through the swing and back through the other rod.

5 Switch on the power supply and observe whether a force acts on the swing.

6 Investigate the effects of reversing the current and the magnetic field (separately).

Question

1 List two ways to reverse the force on a current-carrying conductor in a magnetic field

Fleming's left-hand rule

Figure 20.14a uses arrows to represent three important quantities in the demonstration in Figure 20.12:

- the magnetic field of the permanent magnet
- the current
- the force which moves the aluminium strip.

The magnetic field is horizontal between the poles. The current is also horizontal, but at right angles to the field. The force is vertical, so the foil moves down. The three quantities are all at right angles to each other (Figure 20.14a). To remember how they are arranged, physicists use **Fleming's left-hand rule** (Figure 20.14b) This states that if the **thumb** and first two fingers of the left hand are extended at right angles to each other, and the first finger points in the direction of the field, the second finger in the direction of current, then the thumb will indicate the direction of the force.

Fleming's left-hand rule: a rule that gives the relationship between the directions of force, field and current when a current flows across a magnetic field

It is worth practising holding your thumb and first two fingers at right angles like this. It takes time to get this right. Then learn what each finger represents:

- the First finger is Field
- the seCond finger is Current
- the thuMb is force or Motion.

We use Fleming's left-hand rule to predict the direction of the force on a current-carrying conductor in a magnetic field By keeping your thumb and fingers at right angles to each other, you can show that reversing the direction of the current or field reverses the direction of the force. (Do not try changing the direction of individual fingers. You have to twist your whole hand around at the wrist.)

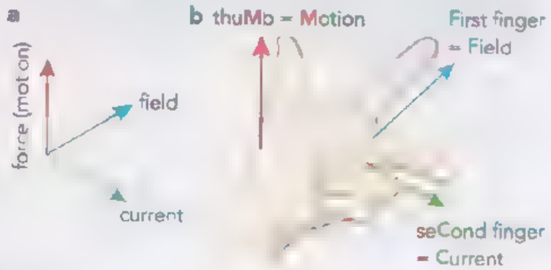


Figure 20.14a: Force, field and current are at right angles to each other. **b:** Fleming's left-hand rule

The motor effect in action – the loudspeaker

Figure 20.15 shows a loudspeaker. This creates a sound wave in the air due to the vibrating paper cone. The cone is attached to a coil of copper wire which fits loosely over

the centre of a cylindrical magnet. The coil is, therefore, a conductor which is free to move in a magnetic field. When a current flows in the coil, the coil and cone will move.

The current input varies with the sound being produced a varying signal is received from a microphone, MP3 player or similar. The changing current causes the coil and cone to move to and fro and produce a sound wave.

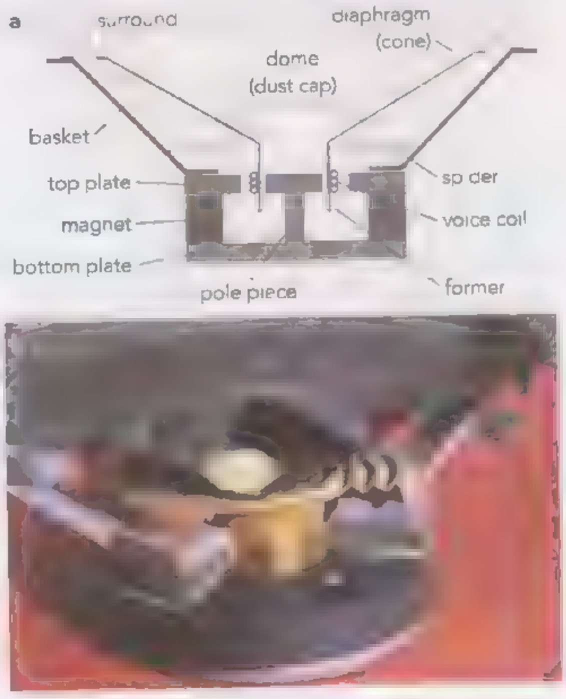


Figure 20.15a: Diagram of a loudspeaker. b: This loudspeaker has been dismantled so you can see the permanent magnet and the coil.

20.3 Electric motors

Figure 20.16a: The type of motor used in school laboratories. b: The motor taken apart. Notice the copper coils and the curved magnets inside the casing and the coil.

The movement created in the motor effect experiments is not very useful. The conductor moves out of the field and the effect is over. A motor is designed to use the motor effect to create a turning movement.

Figure 20.17: This model is used to show the principles of operation of an electric motor

The turning movement happens because the wire is coiled. Look at the coil in Figure 20.17. The current flows up the right-hand side of the coil and down the left. This means that the forces on the two wires are in opposite directions. The right-hand wire moves up and the left-hand wire moves down. This makes the coil spin. The brushes and commutator make sure that the current always flows the same way round the coil, in this case, anticlockwise.

commutator: a device used to allow current to flow to and from the coil of a d.c. motor or generator

For a d.c. motor like this (Figure 20.17) to be of any use, its axle must be connected to something that is to be turned - a wheel, a pulley or a pump, for example. This model motor is not very powerful. The turning effect can be increased by:

- increasing the number of turns of wire in the coil
- increasing the current
- increasing the strength of the magnetic field

Questions

6 Describe the energy transfers that happen in:

a an electric motor

b a loudspeaker.

7 Figure 20.18 shows a type of ammeter. Copy and complete the sentences to explain how it works.

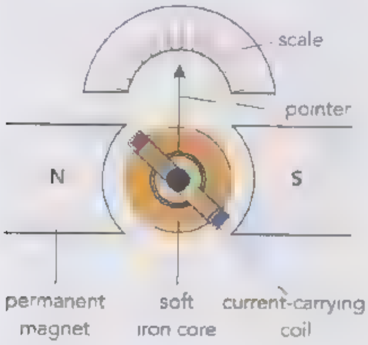


Figure 20.18

When ______ passes through the coil, it experiences a ______ because it is in a magnetic ______. This causes the coil to rotate.

When the current increases, the force will be ______ and so the pointer will move ______ on the scale.

8 A student does an experiment to show the motor effect using the apparatus shown in Figure 20.19. The wire moves upwards.

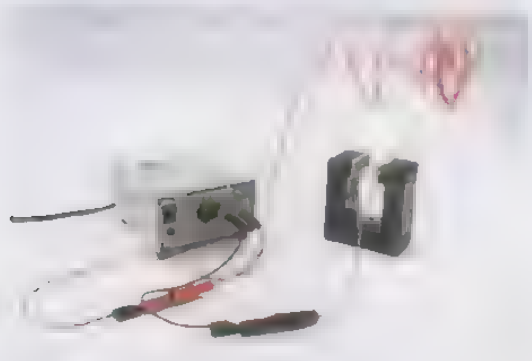


Figure 20.19

a Describe two ways in which the student could reverse the effect to make the wire move downwards.

b The student moves the wire so that it passes from the north to the south pole of the magnet as shown in Figure 20.20. Explain why the wire does not move

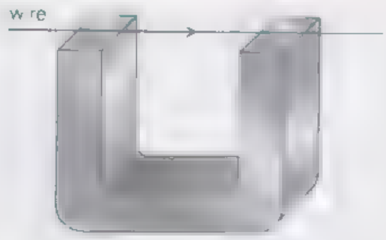


Figure 20.20

Electric motors explained

We can apply Fleming's left-hand rule to an electric motor. Figure 20.21a shows a simple electric motor with its coil horizontal in a horizontal magnetic field. The coil is rectangular. What forces act on each of its four sides?

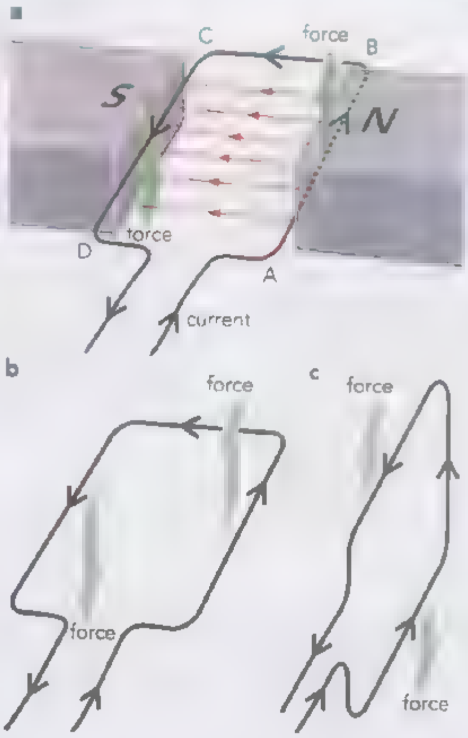


Figure 20.21a: A simple electric motor. Only the two longer sides experience a force, since their currents cut across the magnetic field. **b:** The two forces provide the turning effect needed to make the coil rotate. **c:** When the coil is in the vertical position, the forces have no turning effect.

- Side AB: the current flows from A to B, across the magnetic field. Fleming's left-hand rule shows that a force acts on it, vertically upwards.
- Side CD: the current is flowing in the opposite direction to the current in AB, so the force on CD is in the opposite direction, downwards.
- Sides BC and DA: the current here is parallel to the field. Since it does not cross the field, there is no force on these sides.

Figure 20.21b shows a simplified view of the coil. The two forces acting on it are shown. They cause the coil to turn anticlockwise. The two forces provide a turning effect (or torque), which causes the motor to spin. From Figure 20.21c, you can see that the forces will not turn the coil when it is vertical. This is where we have to rely on the coil's momentum to carry it further round.

Keeping the motor turning

As the momentum of the coil carries it round, the wires AB and CD swap positions. The commutator spins with the coil. The brushes do not move. This means that, in the motor in Figure 20.21, current always flows in on the right, and anticlockwise round the coil. This means that the motor keeps turning in the same direction.

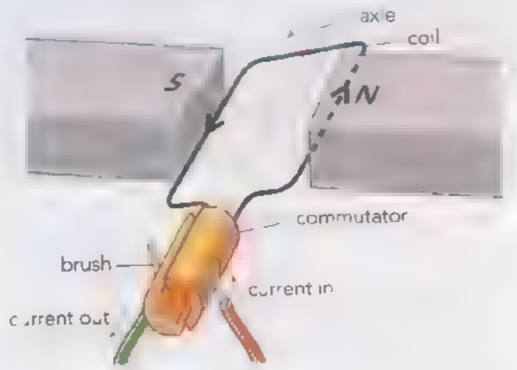


Figure 20.22: A spinning electric motor. Every half turn the commutator reverses the connections to the power supply, so that the motor keeps turning in the same direction.

The diagrams show the coil as if it were a single turn of wire. In practice, the coil might have hundreds of turns of wire, resulting in forces hundreds of times as great. A coil causes the current to flow across the magnetic field many times, and each time it feels a force. A coil is simply a way of multiplying the effect that would be experienced using a single length of wire.

Questions

9 For Fleming's left-hand rule, write down the three quantities that are at 90° to each other, and, next to each one, write down the finger that represents it.

10 In Figure 20.23, crosses represent a magnetic field into the page and dots represent a field coming out of the page. In each case, use Fleming's left-hand rule to determine the direction of the force on the wire.

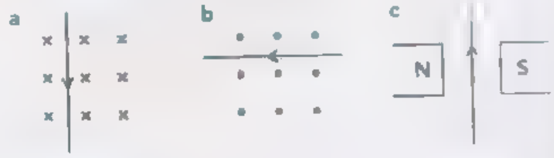


Figure 20.23

11 List two ways to increase the force on a current-carrying conductor in a magnetic field.

12 Describe the motion that would be seen if the coil in a motor was attached directly to a d.c. power supply without a commutator.

20.4 Beams of charged particles and magnetic fields

A magnetic field can also be used to deflect a beam of electrons, or any electrically charged particles. This can be demonstrated in the laboratory using a vacuum tube (Figure 20.24). There is a force on the electrons in the same way as we saw earlier for a current-carrying conductor in a magnetic field. The direction of the force is given by Fleming's left-hand rule, but remember that the conventional current is in the opposite direction to the electron flow. In Figure 20.24, an electron beam is travelling from left to right in a vacuum tube. This is equivalent to a conventional current flowing from right to left. In Figure 20.24a the north pole of a magnet is held behind the tube, giving a field which comes out of the page. Fleming's left-hand rule shows that the force on the beam is upwards. Figure 20.24a shows the effect of this force. Figure 20.24b shows the effect of reversing the direction of the field.

Figure 20.24: An electron beam in a vacuum tube, being deflected by a magnetic field. As with a current in a wire, reversing the field reverses the force on the beam of electrons.

This effect is used in particle accelerators such as those at CERN in Switzerland, to focus and to divert beams of charged particles. The particles travel at enormously high speeds and so have a lot of kinetic energy. Huge fields are needed to divert them.

Figure 20.25: This giant magnet, which has a mass of 1920 tonnes, was installed 100 metres below ground in a 27 km tunnel at CERN to provide a magnetic field for a giant particle detector.

PROJECT

Motors everywhere

This kitchen contains at least three electric motors. Identify where they are.

In this project you will research either the uses of motors or the motor effect in different situations.

Option 1

Collect pictures of things which use motors. These can be photos, drawings or pictures from the Internet or catalogues. Try to find pictures covering all the following uses of motors:

- kitchen appliances
- hair and beauty appliances
- transportation.
- medicine
- industry
- music

Identify the energy transfers that happen in each appliance, including any waste energy.

Use your pictures to create a poster about motors. Include diagrams and text to explain how motors work, and how some motors are constructed to make them stronger than others. Include the words: magnetic field, current, electromagnet, force and coil.

CONTINUED

Option 2

The motor effect is used in other devices as well

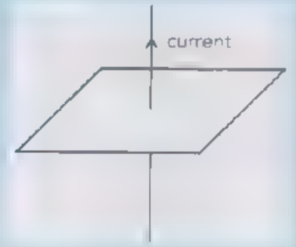
[illegible] or particle [illegible] (which [illegible]

- detailed diagrams showing at least three uses of the motor effect
- [illegible]
- follow up questions (with answers) to check your audience understand your presentatio[n] [illegible] your questions).

There is a magnetic field around a current-carrying conductor
The magnetic effect of a current has many practical uses including the electric bell and relay
The field around a wire is strongest near the wire
The field in a solenoid is strongest inside the coil
The strength and direction of the field depends on the size and direction of the current
When a current flows through a conductor in a magnetic field, there is a force on the conductor. This is called the motor effect
The direction of the force can be reversed by reversing the field or the current
A coiled conductor in a magnetic field experiences a turning force. This is the basis of the electric motor
The strength of a motor can be increased by increasing the field, the current or the number of turns on the coil
Fleming's left-hand rule allows you to find the direction of the force on a current-carrying conductor
Fleming's left-hand rule can also be used to find the direction of the force on a beam of charged particles in a magnetic field
An electric motor uses a split ring commutator to produce continuous rotation

CONTINUED

1 Current flows up a wire as shown in the diagram. What will the magnetic field look like? **[1]**



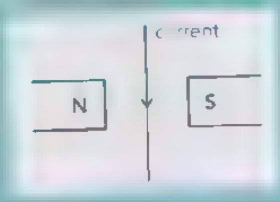
A straight lines from left to right
B straight lines from right to left
C clockwise circles
D anticlockwise circles

2 Which line gives the correct material for the armature of a relay, and the property which makes it suitable? **[1]**

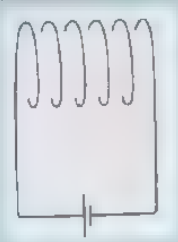
	Material	Property
A	copper	good conductor
B	soft iron	bendy
C	copper	easily magnetised
D	soft iron	easily demagnetised

3 Which of the following pairs of changes will both increase the strength of an electric motor? **[1]**

A Reversing the magnetic field and increasing the number of turns on the coil
B Increasing the number of turns on the coil and reversing the direction of the current
C Reversing the direction of the current and reversing the magnetic field
D Using a more powerful magnet and increasing the number of turns on the coil



5 a Copy the diagram and draw the magnetic field of the solenoid. Show both the shape and the direction of the field lines. [3]



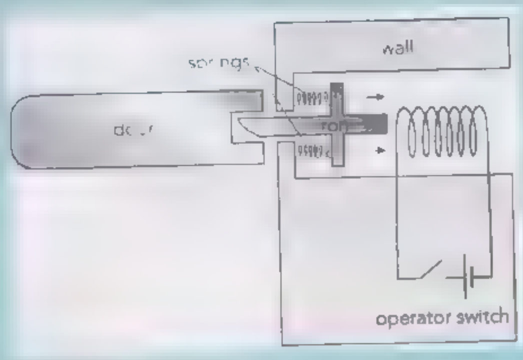
b What would happen to the magnetic field if the connections to the cell were reversed? [1]

c A student placed two metal bars inside the solenoid. When current was flowing the bars moved apart. why. [2]

d what metal the bars were made from and why. [2]

[Total: 8]

6 The diagram shows an electromagnetic door opening system.



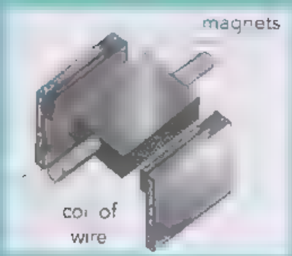
what happens when the operator closes the switch. [3]

set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

suggest apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations

describe state the points of a topic/give characteristics and main features


wire connected to
d.c power supply


magnets
coi of
wire

CONTINUED

[illegible]

[illegible] [2]

[illegible] [1]

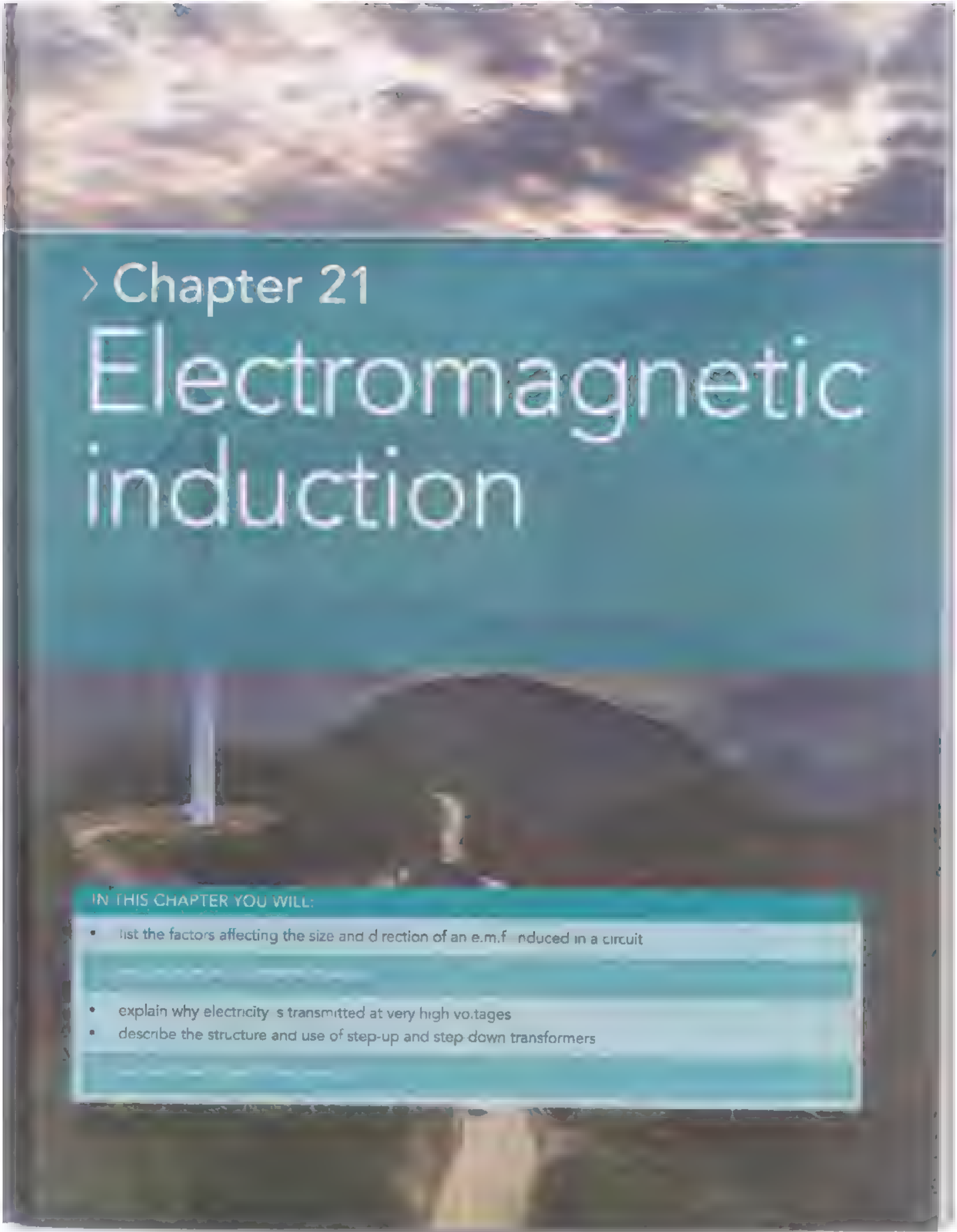
[illegible]

determine: establish an answer using the information available

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Describe an experiment to show the field around a straight wire and a solenoid when they carry current.	20.1			
Draw the pattern and direction of these fields.	20.1			
Describe the factors that affect the direction and strength of these fields.	20.1			
Describe the action of an electric relay and a loudspeaker	20.1			
Interpret diagrams of other devices using electromagnets	20.1			
State that a current-carrying conductor in a magnetic field experiences a force	20.2			
Use Fleming's left-hand rule to find the direction of this force.	20.2			
List three ways of increasing the strength of an electric motor	20.3			
Describe how an electric motor produces a turning effect, including the function of the brushes and split-ring commutator.	20.3			
Recall that a beam of charged particles in a magnetic field experiences a force and determine the direction of this force.	20.4			



> Chapter 21

Electromagnetic induction

IN THIS CHAPTER YOU WILL:

- list the factors affecting the size and direction of an e.m.f. induced in a circuit
- explain why electricity is transmitted at very high voltages
- describe the structure and use of step-up and step-down transformers

[illegible]

In Chapter 18 you learnt about the electrical quantities we can measure or calculate. These include: current, potential difference, resistance, charge, energy, power and electro-motive force.

For each quantity, write a definition, the letter used to represent the quantity in an equation (for example, *l* for length), and its unit.

Write down all the equations you know which involve these quantities.

In a small group, play a game to check your learning:

Create a set of cards. There should be one card for the name of each quantity, one card for the unit of each quantity, one card for time, and one card for seconds.

Place the cards face down in a pack. The first player turns two cards over. If they can connect the cards in a sentence or equation, they score a point.

Return the cards to the pack, mix them up, and then the next player takes their turn.

For example, if a player picks 'ohm' and 'current', they could say: 'when the resistance in ohms increases, the current drops'. If a student makes an incorrect link, other players can score a point by spotting the mistake and giving a correct answer.

WHY MUST ELECTRIC GUITARS HAVE METAL [illegible]

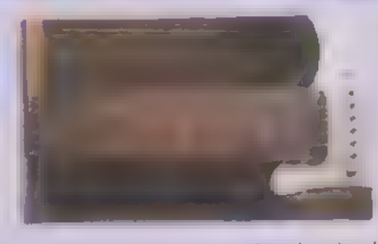


Figure 21.1: The metal circles (on the white bar below the strings of this electric guitar) pick up sound vibrations. Notice that the strings do not touch the pickup.

We saw in Chapter 20 that a current flowing in a magnetic field experiences a force which can make it move. In this chapter we will investigate the reverse process. When a conductor and magnetic field move relative to each other, a current flows in the conductor. This is the principle behind the operation of power stations.

This effect is also used to pick up sound vibrations in an electric guitar. The guitar strings are magnetised by a permanent magnet in the pick-up below the strings. This is why they must be made of a magnetic metal such as nickel or steel. The pick-up device – the white bar below the strings in Figure 21.1 – also contains coils of copper wire which are wrapped around the permanent magnets. The strings vibrate when the guitar is played. The amplitude and frequency of these vibrations depend on the note being played. We now have relative movement between a conductor (the coils) and a field (around the magnetised strings) and so a current flows in the coils. This current is amplified and fed to a loudspeaker. The size and frequency of the current depends on the vibrations of the strings. This allows music to be played.

Figure 21.2: How the pickup in a guitar works

Figure 21.2 shows the field lines from the permanent magnet which magnetises the metal strings. The changing current generated in the coil is passed to the speaker which contains a magnet. As the changing current flows, the speaker cone moves, producing sound – this is the motor effect.

Discussion questions

1 The guitar pickup does not touch the strings. Explain why this is an advantage.

2 The electromagnetic pickup shown in Figure 21.2 would not work for a guitar with nylon strings. Explain why.

3 Describe the energy changes involved from the guitar being strummed to the sound being heard from the speaker.

21.1 Generating electricity

A motor is a device that transfers energy by an electrical current into a mechanical (kinetic) energy store. An electrical generator does the opposite – it transfers energy from a mechanical energy store by an electrical current. An electric motor can be used in reverse to generate electricity. If you connect an electric motor to a lamp and spin its axle, the lamp will light, showing that you have generated a voltage which causes a current to flow through the lamp (Figure 21.3).

Figure 21.3: A motor can act as a generator. Spin the motor and the lamp lights, showing that an induced current flows around the circuit

Inside the motor, the coil is spinning around in the magnetic field provided by the permanent magnets. The result is that a current flows in the coil, and this is shown by the lamp. We say that the current has been induced, and the motor is acting as a generator.

There are many different designs of generator, just as there are many different designs of electric motor. Generators in power stations supply electricity to communities. If you have a bicycle, you may have a generator of a different sort – a dynamo – for powering the lights.

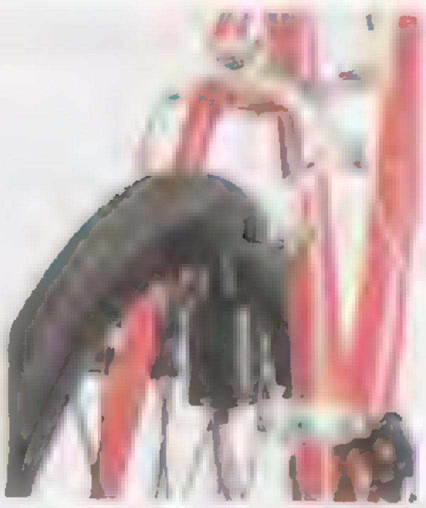


Figure 21.4: The dynamo rubs against the wheel causing it to turn. This generates current to light the bicycle lamp.

The power station generators shown in Figure 21.10 generate alternating current at a voltage of about 25 kV. The turbines are made to spin by the high-pressure steam from the boiler. The generator is on the same axle as the turbine, so it spins too. A coil inside the generator spins around inside some fixed electromagnets, which provide the magnetic field. A large current is then induced in the rotating coil, and this is the current that the power station supplies to consumers.

All of these generators have three things in common:

- a magnetic field (provided by magnets or electromagnets)
- a coil of wire (fixed or moving)
- movement (the coil and magnetic field move relative to one another).

When the coil and the magnetic field move relative to each other, a current flows in the coil if it is part of a complete circuit. This is known as an induced current. If the generator is not connected up to a circuit, there will be an **induced e.m.f.** (or **induced voltage**) across its ends, ready to make a current flow around a circuit.

induced e.m.f. (or induced voltage) the e.m.f. created in a conductor when it cuts through magnetic field lines

The principles of electromagnetic induction

The process of generating electricity from motion is called **electromagnetic induction**. The science of electromagnetism was largely developed by Michael Faraday. He invented the idea of the magnetic field and drew field lines to represent it. He also invented the first electric motor. Then he extended his studies to show how the motor effect could work in reverse to generate electricity. In this section, we will look at the principles of electromagnetic induction that Faraday discovered.

As we have seen, a coil of wire and a magnet moving relative to each other are needed to induce a voltage across the ends of a wire. If the coil is part of a complete circuit, the induced e.m.f. will make an induced current flow around the circuit.

In fact, you do not need to use a coil – a single wire is enough to induce an e.m.f., as shown in Figure 21.5a. The wire is connected to a sensitive meter to show when a current is flowing.

- Move the wire down between the poles of the magnet and a current flows.
- Move the wire back upwards and a current flows in the opposite direction.
- Alternatively, the wire can be kept stationary and the magnet moved up and down. Again, a current will flow.

You can see similar effects using a magnet and a coil (Figure 21.5b). Pushing the magnet into and out of the coil induces a current, which flows back and forth in the coil. Here are two further observations:

- Reverse the magnet to use the opposite pole and the current flows in the opposite direction.
- Hold the magnet stationary next to the wire or coil and no current flows. They must move relative to each other, or nothing will happen.

In these experiments it helps to use a centre-zero meter. Then, when the needle moves to the left, it shows that the current is flowing one way; when it moves to the right, the current is flowing the other way.

electromagnetic induction: the production of an e.m.f across an electrical conductor when there is relative movement between the conductor and a magnetic field

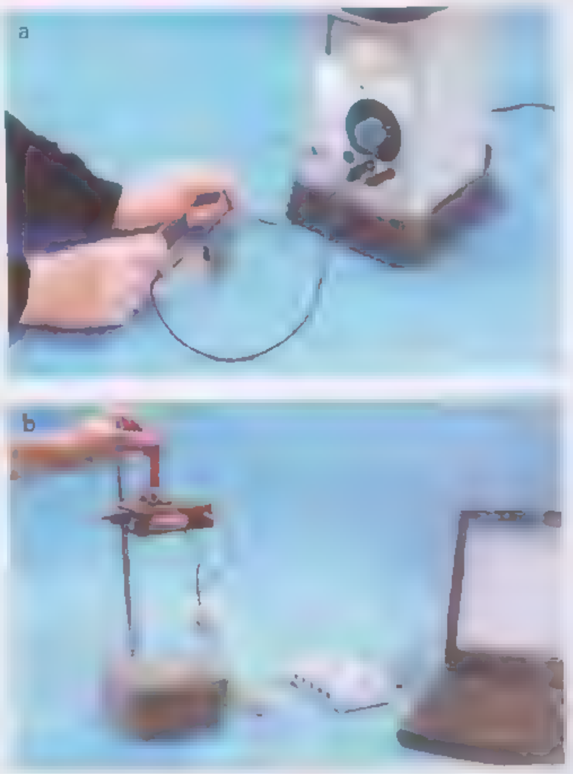


Figure 21.5a: Move a wire up and down between the poles of a stationary magnet and an induced current will flow.
b: Similarly, move a magnet into and out of a coil of wire and an induced current will again flow.

Increasing the induced e.m.f.

There are three ways to increase the e.m.f. induced in a coil or wire:

- use a stronger magnet
- move the wire or coil more quickly relative to the magnet
- use a coil with more turns of wire. Each turn of wire will have an e.m.f. induced in it, and these all add together to give a bigger e.m.f.

EXPERIMENTAL SKILLS 21.1

Inducing electricity

In this experiment you will induce an e.m f. and investigate the factors which affect the induced e.m.f., including the factors affecting the size and direction of the e.m.f. induced when a conductor moves relative to a magnetic field.

Safety: Some sensitive meters have a locking mechanism which prevents them being damaged during movement. Check your meter before you begin

Getting started

Look carefully at the meter you are using. Explain:

- why zero is at the centre of the scale
- how you can tell it is a very sensitive meter

You will need:

- thin insulated wire
- strong bar magnet
- 2 magnadur magnets and a yoke
- sensitive, centre-zero ammeter or voltmeter

Method

1. Coil 2.0 metres of thin insulated wire with bare ends to make a solenoid approximately 5 cm in diameter. The coil can be flat as shown in Figure 21.6 rather than long.
2. Connect the ends of the coil to the terminals of a sensitive voltmeter or ammeter.
3. Bring one pole of a bar magnet towards and into the centre of the coil. Observe the reading on the meter.

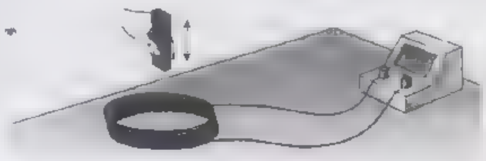


Figure 21.6: Experimental set up.

4. Now investigate how the reading on the meter changes in different circumstances.
   - Move the bar magnet at different speeds into the coil.
   - Use the opposite pole of the bar magnet.
   - Move the bar magnet out of the coil
   - Hold the bar magnet stationary at different distances from the coil
5. Straighten out the wire. Keep the ends connected to the meter.
6. Mount two magnadur magnets on a yoke. Ensure that opposite poles are facing each other so that there is a strong magnetic field between the magnets.
7. Hold a section of the wire, approximately 10 cm in length, between your two hands. Move the wire downwards through the field (Figure 21.7). Observe the reading on the meter.

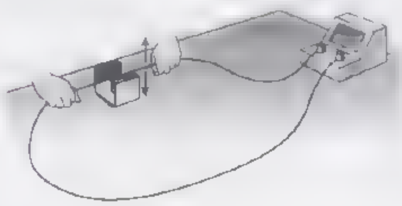


Figure 21.7: Experimental set up (part 2)

8. Now investigate how the reading on the meter changes in different circumstances.
   - Move the wire at different speeds through the magnetic field.
   - Reverse the direction of the magnetic field.
   - Move the wire out of the magnetic field.
   - Hold the wire stationary in the magnetic field.

CONTINUED

Question

1 Copy and complete these sentences to record your observations:

An e.m.f. is induced in a conductor in a magnetic field if either the ____ or the ______ move across the other.

The size of the e.m.f. induced in a coil can be increased by increasing ______, ______ or ______.

The direction of the e.m.f. can be ______ by reversing the field or the direction of movement

Questions

1 Which of the following would not induce a current:

- **A** moving a wire between the poles of a magnet
- **B** taking a bar magnet out of a coil or wire
- **C** holding a wire between the poles of a magnet
- **D** spinning a coil or wire in a magnetic field.

2 Marcus holds a piece of copper wire which is connected to an ammeter between the poles of a magnet, but he does not get a reading on the ammeter. What should he do to make a current flow?

3 A student moves a bar magnet into a coil of wire and a current flows. Describe two changes which would make the current flow in the opposite direction.

4 An a.c generator and a cell can both be used to light a bulb. Describe how the current flowing through the bulb is different in each case.

Induction and field lines

We can understand electromagnetic induction by thinking about magnetic field lines. Figure 21.8 shows the field lines between the poles of a horseshoe magnet. As the wire is moved down between the poles of the magnet, it cuts the field lines of the magnet. Cutting the field lines induces the current.

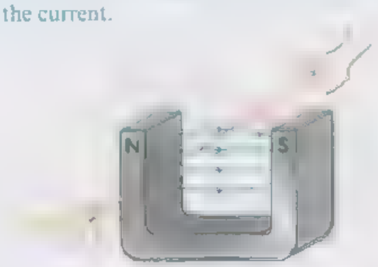


Figure 21.8: As the wire cuts through the field lines, an e.m.f. is induced in it. If the wire is part of a complete circuit, a current will flow

This idea helps us to understand the factors that affect the magnitude and direction of the induced e.m.f.

- When the magnet is stationary, there is no cutting of field lines and so no e.m.f. is induced
- When the magnet is further from the wire, the field lines are further apart and so fewer are cut, giving a smaller e.m.f.
- When the magnet is moved quickly, the lines are cut more quickly and a bigger e.m.f. is induced
- A coil gives a bigger effect than a single wire, because each turn of wire cuts the magnetic field lines. This means that each contributes to the induced e.m.f.

Fleming's right-hand rule

We have seen that, when a wire is moved so that it cuts across a magnetic field, a current is induced in the wire. How can we work out the direction of the current? [illegible] current flows in a magnetic field, there is a force on it so that it moves. The directions of force, field and current were given by Fleming's left-hand rule. It is not surprising to find that, in the case of electromagnetic induction, the directions are given by **Fleming's right-hand rule**. As shown in Figure 21.9, the thumb and first two fingers show the directions of the same quantities. Take care to use the correct hand.

Fleming's right-hand rule: a rule that gives the relationship between the directions of force, field and current when a current flows across a magnetic field

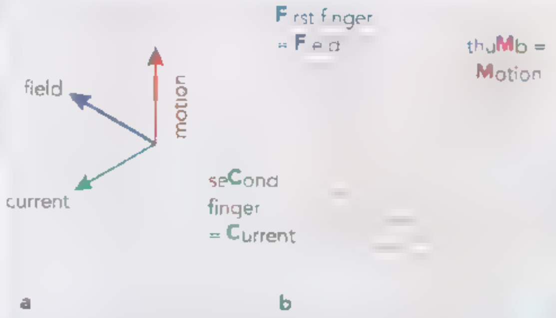


Figure 21.9a. When a current is induced in a wire, motion, field and current are at right angles to each other **b:** Fleming's right-hand rule is used to work out the direction of the induced current.

An a.c. generator

Faraday's discovery of electromagnetic induction led to the development of the electricity supply industry. In particular, it allowed engineers to design generators that could supply electricity. At first, this was only done on a small scale, but gradually generators got bigger and bigger, until, like the ones shown in Figure 21.10, they were capable of supplying the electricity demands of thousands of homes.

Figure 21.10: The turbine and generator in the generating hall of a nuclear power station. The turbines are fed by high-pressure steam in pipes.

A generator of this type produces alternating current (a.c.). Alternating current flows first one way then the other as the coils turn in the magnetic field.

Figure 21.11 shows a simple a.c. generator, which produces alternating current. In principle, an a.c. generator is like a d.c. motor, working in reverse. The axle is made to turn so that the coil spins around in the magnetic field, and a current is induced. The other difference is in the way the coil is connected to the circuit beyond. A d.c. motor uses a split-ring commutator whereas an a.c. generator uses slip rings. The slip rings rotate with the coil. The brushes rub against the slip rings and so have the same e.m.f. as the sides of the coil.

a.c. generator: a device such as a dynamo used to generate alternating current

slip rings: a device used to allow current to flow to and from the coil of an a.c. generator

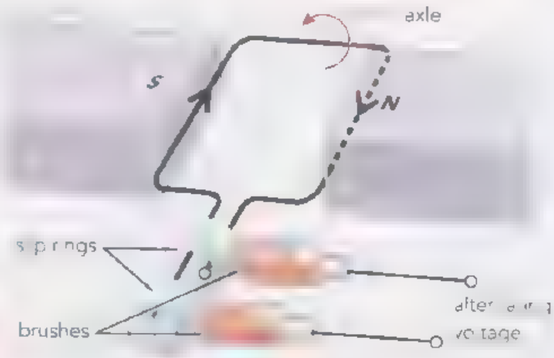


Figure 21.11: A simple a.c. generator works like a motor in reverse. The slip rings and brushes are used to connect the alternating current to the external circuit.

Why does this generator produce alternating current? As the coil rotates, each side of the coil passes first the magnetic north pole and then the south pole.

Figure 21.12 shows a graph of this. When the coil is horizontal, it cuts through the field lines inducing a voltage. As it turns to vertical, it cuts fewer field lines so the voltage decreases to zero. As it continues back to horizontal it cuts through the field lines in the opposite direction, giving a peak voltage in the opposite direction.

This means that the induced current flows first one way and then the other. In other words, the current in the coil is alternating.

The current flows out through the slip rings. Each ring is connected to one end of the coil, so the alternating current flows out through the brushes, which press against the rings.

There are four ways of increasing the voltage generated by an a.c. generator like the one shown in Figure 21.11:

- turn the coil more rapidly
- use a coil with more turns of wire
- use a coil with a bigger area
- use stronger magnets.

Each of these changes increases the rate at which magnetic field lines are cut, and so the induced e.m.f. is greater. For the a.c. generator shown in Figure 21.11, each revolution of the coil generates one cycle of alternating current. Spin the coil 50 times each second and the a.c. generated has a frequency of 50 Hz.

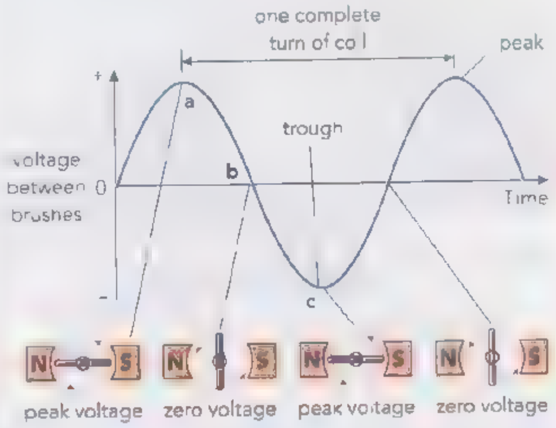


Figure 21.12: A graph to represent an alternating voltage. As the coil turns, the voltage reaches a peak in one direction, decreases to zero, then reverses.

Figure 21.12 shows how the e.m.f. produced by an a.c. generator varies as the coil turns. If we think about how the coil cuts through magnetic field lines, we can understand why the a.c. graph varies between positive and negative values. With the coil in the horizontal position, as shown in position a, its two long sides are cutting rapidly through the magnetic field lines. This gives a large induced e.m.f., corresponding to a peak in the a.c. graph. When the coil is vertical (position b), its long sides are moving along the field lines, so they are not cutting them. This gives no induced e.m.f., a zero point on the a.c. graph. When the coil has turned through 180° to position c, it will be cutting field lines quickly again, but in the opposite direction, so the induced e.m.f. will again be large, but this time it will be negative – this corresponds to a trough on the graph.

Direction of the induced e.m.f.

How is the direction of an induced current determined? The answer is that the current (like all currents) has a magnetic field around it. This field always pushes back against the field that is inducing the current. So, for the coil shown in Figure 21.13, when the magnet's north pole is pushed towards the coil, the current flows to produce a north pole at the end of the coil nearest the magnet. These two north poles repel each other. This means that you have to push the magnet towards the coil and that you have to do work. The energy you use in pushing the magnet is transferred to the current. That is where the energy carried by the current comes from. It comes from the work done in making a conductor cut through magnetic field lines.

An induced current always flows in such a way that its magnetic field opposes the change that causes it. This is known as **Lenz's law**.

Lenz's law: the direction of an induced current always opposes the change in the circuit or the magnetic field that produces it

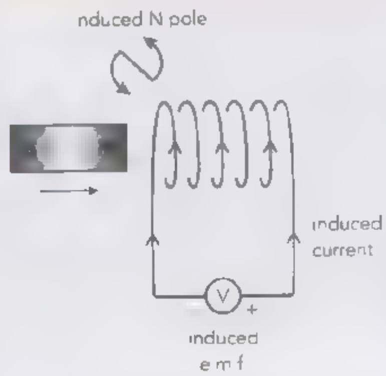


Figure 21.13: Consider a bar magnet being moved into a coil north pole first. Lenz's law tells us that the e.m.f. induced will oppose this. Therefore, the end the magnet approaches must become a north pole, to repel the approaching north pole. This means that the current must flow anticlockwise at that end of the coil.

Questions

5 A student moves the north pole of a magnet towards a coil of wire (as shown in Figure 21.13), so that an induced current flows. State two ways in which the student could cause a bigger induced current to flow.

6 Draw a diagram similar to Figure 21.13 to show what happens when the magnet is moved away from the coil. (Hint: remember, the induced current will oppose this change.)

ACTIVITY 21.1

Generating fitness

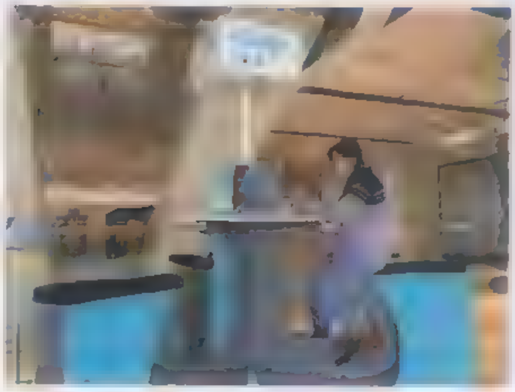


Figure 21.14: Using an exercise bike to charge a mobile phone

The woman in Figure 21.14 is charging her mobile phone. As she pedals the exercise bike, she turns a generator to induce a current which is used to charge her phone.

Produce a poster to attract customers to use a bike charger in a public place. You should include information about how the system helps to:

- save money
- improve the user's health
- protect the environment.

You should also include a more detailed section for the user to read as they pedal. This should explain how the system works and advise the customer how to charge their phone as quickly as possible.

21.2 Power lines and transformers

Figure 21.15: Electricity is usually generated at a distance from where it is used. If you look on a map, you may be able to trace the power lines that bring electrical power to your neighbourhood.

Power stations may be 100 km or more from the places where the electricity they generate is used. This electricity must be distributed around the country.

High-voltage electricity leaves the power station. Its voltage may be as high as 1 million volts. To avoid danger to people, it is usually carried in cables called **power lines** slung high above the ground between tall pylons. Lines of pylons carry wires across the countryside, heading for the urban and industrial areas that need the power (Figure 21.16). This is a country's **national grid**.

KEY WORDS

power lines: cables used to carry electricity from power stations to consumers

national grid: the system of power lines, pylons and transformers used to carry electricity around a country

When the power lines approach the area where the power is to be used, they enter a local distribution centre. Here the voltage is reduced to a less hazardous level, and the power is sent through more cables (overhead or underground) to local substations. In the substation, the voltage is reduced to the local supply voltage, typically 230 V. Wherever you live, there is likely to be a substation

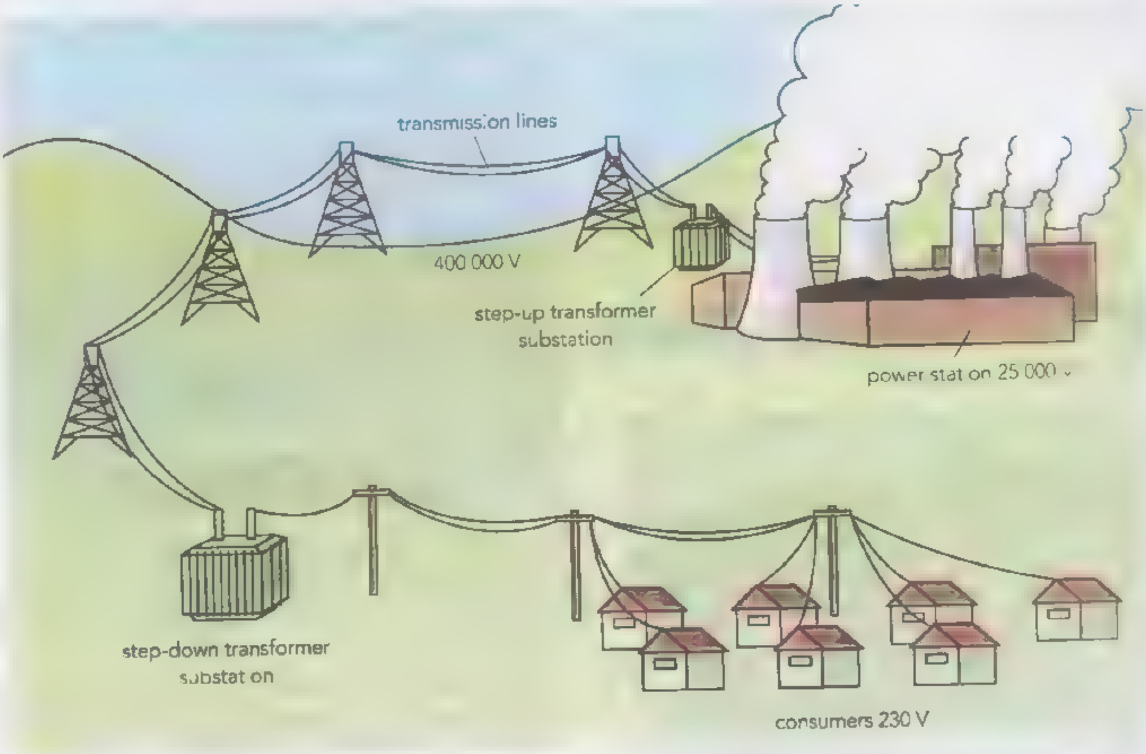


Figure 21.16: In a national grid, voltages are increased to reduce energy losses, then reduced to a relatively safe level.

in the neighbourhood. It may be in a securely locked building, or the electrical equipment may be surrounded by fencing, which carries notices warning of the hazard (Figure 21.17).

Figure 21.17: An electricity substation has warning signs like this to indicate the extreme hazard of entering the substation.

From the substation, electricity is distributed to houses, shops, etc. In some countries, the power is carried in cables buried underground. Other countries use tall poles and overhead wires.

Why use high voltages?

The high voltages used to transmit electrical power around a country are dangerous. That is why the cables that carry the power are supported high above people, traffic and buildings on tall pylons. Sometimes the cables are buried underground, but this is much more expensive, and the cables must be safely insulated. The reason for using high voltages is to reduce the loss of energy due to the cables heating up. This heating happens much more when the same power is transmitted at a lower voltage.

Transformers

A **transformer** is a device used to increase or decrease the voltage of an electricity supply. They are designed

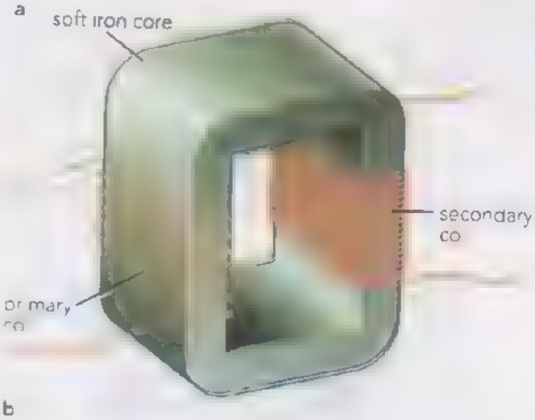
to be as efficient as possible (up to 99.9% efficient). This is because the electricity we use may have passed through as many as ten transformers before it reaches us from the power station. A loss of 1% of energy in each transformer would represent a total waste of 10% of the energy leaving the power station.

Power stations typically generate electricity at 25 kV This has to be converted to the grid voltage (typically 400 kV) using transformers. This is known as stepping up the voltage

Figure 21.18a shows the construction of a suitable transformer. Every transformer has three parts:

- A **primary coil**: the incoming voltage V_p is connected across this coil
- A **secondary coil**: this provides the voltage V_s to the external circuit.
- An iron core: this links the two coils.

a



b

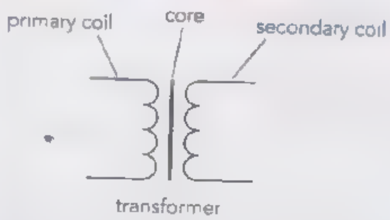


Figure 21.18a: The structure of a transformer. This is a step-up transformer because there are more turns on the secondary coil than on the primary. If the connections to it were reversed, it would be a step-down transformer. **b:** The circuit symbol for a transformer shows the two coils with the core between them

Notice that there is no electrical connection between the two coils. They are linked together only by the soft iron core The wires are insulated so no current flows from one coil to the other Notice also that the voltages are both alternating voltages. Transformers only work with a.c. All they do is change the size of an a.c. voltage.

The power station transformer described earlier steps up the voltage from 25 kV to 400 kV it is increased by a factor of 16. To step up the voltage by a factor of 16, there must be 16 times as many turns on the secondary coil as on the primary coil. By comparing the numbers of turns on the two coils we can tell how the voltage will be changed

- A **step-up transformer** increases the voltage. There are more turns on the secondary coil than on the primary coil.
- A **step-down transformer** reduces the voltage. There are fewer turns on the secondary coil than on the primary coil

transformer: a device used to change voltage of an a.c electricity supply

primary coil: the input coil of a transformer

secondary coil: the output coil of a transformer

step-up transformer: a transformer which increases the voltage of an a.c. supply

step-down transformer: a transformer which decreases the voltage of an a.c. supply

Note that, when the voltage is stepped up, the current is stepped down, and when the voltage is stepped down, the current is stepped up.

The ratio of the number of turns tells us the factor by which the voltage will be changed. We can write an equation, known as the transformer equation, relating the two voltages, V_p and V_s, to the numbers of turns on each coil, N_p and N_s:

$$\frac{\text{voltage across primary coil}}{\text{voltage across secondary coil}} = \frac{\text{number of turns on primary}}{\text{number of turns on secondary}}$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

[illegible]

There are very large transformers between power stations to the transmission cables.

One of these transformers has 800 turns on its primary coil and 16 000 turns on its secondary coil. The voltage across its primary coil is 25 kV.

a State what type of transformer this is.

b Calculate the voltage across its secondary coil.

Step 1: Write down what you know: The transformer has more turns on the secondary coil than the primary so it is a step-up transformer. This means the voltage should increase. Use this to check your answer to the next part.

Step 2: Draw a simple transformer as shown in Figure 21.19 and mark on it the information given in the question.

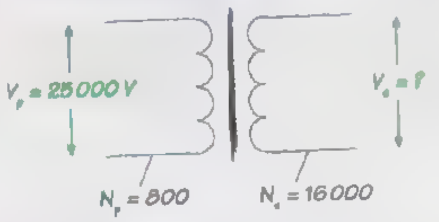


Figure 21.19: Transformer symbol with the quantities given in the question

Step 3: Write down the transformer equation.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Step 4: Substitute in the values from the question.

$$\frac{25\,000\text{ V}}{V_s} = \frac{800}{16\,000}$$

Step 5: Rearrange the equation to find V_s.

$$V_s = \frac{25\,000\text{ V} \times 16\,000}{800}$$

$$= 500\,000\text{ V}$$

Check that this is greater than the primary voltage as expected.

Answer

a step-up transformer

b $V_s = 500\,000$ V

It is often useful to do a quick mental calculation first. For example, if a transformer decreases voltage from 230 V to 60 V, it has reduced it by about a quarter. This means the secondary coil must have roughly a quarter of the number of turns than those on the primary. This is an approximate calculation. It helps you check whether your final answer is sensible.

Questions

7 a Copy and complete these sentences.

Electricity is distributed by the national ____. This consists of substations, cables and ______.

The electricity is transmitted at very high ____ to ______ energy being lost as heat in the cables.

The voltage can be increased or decreased by ____.

b Figure 21.20 shows a transformer.

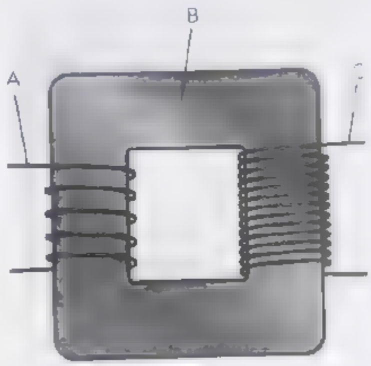


Figure 21.20: A transformer.

Name the parts labelled A, B and C.

c Explain whether this is a step-up or step-down transformer.

8 A transformer has ten turns on the primary coil and five turns on the secondary. A voltage of 12 V is applied across the primary coil.

a Is this a step-up or step-down transformer?

b Use the transformer equation to calculate the output voltage of the transformer.

9 Copy and complete Table 21.1. Calculate the missing information using the transformer equation.

N_p	N_s	V_p	V_s	Step-up or step-down transformer?
10	20		12	step up
10		1.2	12	
	50	240	6	
10 000	20	115 000		

Table 21.1

10 A portable radio has a built-in transformer so that it can work from the mains instead of batteries. Is this a step-up or step-down transformer?

11 A transformer increases the 1100 V from a power station to 132 000 V for transmission. Calculate the number of turns on the primary coil when the secondary coil has 6000 turns.

In these calculations it is useful to think about whether the answer is sensible. Which of the following suggestions are helpful for you? What does this tell you about how you work?

- Draw the transformer and write the numbers on it.
- Draw a diagram of the situation.
- Do a quick approximate calculation first.
- Decide whether the transformer is step-up or step-down, and what this tells you about your answer.

Think about whether you can apply any of these ideas when you do other calculations.

21.3 How transformers work

Transformers only work with alternating current (a.c.). To understand why this is, we need to look at how a transformer works (Figure 21.21). It makes use of electromagnetic induction.

The primary coil has alternating current flowing through it. It is, therefore, an electromagnet, and produces an alternating magnetic field. The core transports this alternating field around to the secondary coil. Now the secondary coil is a conductor in a changing magnetic field. A current is induced in the coil. This is another example of electromagnetic induction at work.

When the secondary coil has only a few turns, the e.m.f. induced across it is small. When it has a lot of turns, the e.m.f. will be large. Hence, to increase the voltage out, we need a secondary coil with many more turns than the primary coil.

When direct current is connected to a transformer, there is no output voltage. This is because the magnetic field produced by the primary coil does not change. With an unchanging field passing through the secondary coil, no voltage is induced in it.

Notice from Figure 21.21 that the magnetic field links the primary and secondary coils. The energy brought by the current in the primary coil is transferred to the secondary coil by the magnetic field. This means that the core must be very good at transferring magnetic energy. A soft magnetic material must be used – usually an alloy of iron with a small amount of silicon. (Recall that soft magnetic materials are ones that can be magnetised and demagnetised easily.)

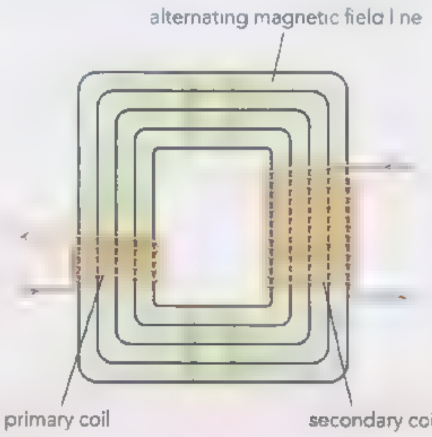


Figure 21.21: The a.c. in the primary coil produces a varying magnetic field in the core. This induces a varying current in the secondary coil.

Even in a well-designed transformer, some energy is lost because of the resistance of the wires, and because the core resists the flow of the changing magnetic field.

Questions

12 a What is the function of the core of a transformer?

b Why must the core be made of a soft magnetic material?

13 Explain why a transformer will not work with direct current.

Calculating current

To transmit a certain power, P, we can use a small current, I, if we transmit the power at high voltage, V. This follows from the equation for electrical power (see Chapter 18):

electrical power $P = IV$

Worked Example 21.2 shows how this works.

Energy saving

There is a good reason for using high voltages. It means that the current flowing in the cables is relatively low, and this wastes less energy. This can be explained as follows.

A consumer needs a certain amount of power. This power can be delivered as:

- high voltage, low current or
- low voltage, high current.

Calculating power losses

When a current flows in a wire or cable, some of the energy it is carrying is lost because of the cable's resistance – the cables get warm. A small current wastes less energy than a high current.

We can calculate the rate of energy loss in the cables, or the power loss, by putting together two equations we met in Chapter 18:

power = current × potential difference or $P = IV$

and

potential difference = current × resistance or $V = IR$

$P = IV$ becomes $P = I(IR)$ or $P = I^2R$

KEY EQUATION

power loss = square of current in the cable × resistance

$P = I^2R$

Electrical engineers do everything they can to reduce the energy losses in the cables. If they can reduce the current to half its value (by doubling the voltage), the losses will be one-quarter of their previous value. This is because power losses in cables are proportional to the square of the current flowing in the cables:

- double the current gives four times the losses
- three times the current gives nine times the losses.

WORKED EXAMPLE 21.2

A 20 kW generator gives an output of 5 kV. This is transmitted to a workshop by cables with a resistance of 20 Ω. Calculate:

a the power loss in the cables

b the effect of using a transformer to increase the output voltage to 20 kV, assuming that the power output remains the same.

When answering this question, it is important to realise there are two different powers involved – the power of the generator and the power loss in the cables.

Step 1: Calculate the current in the wires at 5 kV using the equation:

generator power, $P = IV$

Rearrange the equation and substitute values:

$I = P \div V = 20\,000\text{ W} \div 5000\text{ V} = 4\text{ A}$

Step 2: Calculate the power loss.

power loss, $P = I^2R = (4\text{ A})^2 \times 20\,\Omega = 320\text{ W}$

(this is the answer to part a)

Step 3: Calculate the current in the wires at 20 kV.

$P = IV$

$I = P \div V = 20\,000\text{ W} \div 20\,000\text{ V} = 1\text{ A}$

Step 4: Calculate the power loss.

$P = I^2R = (1\text{ A})^2 \times 20\,\Omega = 20\text{ W}$

Answer

a 320 W

b Using the transformer to decrease the voltage greatly reduces the power loss, from 320 W to 20 W.

From the results of Worked Example 21.2, you can see why electricity is transmitted at high voltages. The higher the voltage, the smaller the current in the cables and so the smaller the energy losses. Increasing the voltage by a factor of four reduces the current by a factor of four. This means that the power lost in the cables is greatly reduced (in fact, it is reduced by a factor of 4^2, which is 16), and so thinner cables can safely be used.

The current flowing in the cables is a flow of coulombs of charge. At high voltage, we have fewer coulombs flowing, but each coulomb carries more energy with it.

Thinking about power

If a transformer is 100% efficient, no power is lost in its coils or core. This is a reasonable approximation, because well designed transformers waste only about 0.1% of the power transferred through them. This allows us to write an equation linking the primary and secondary voltages, V_p and V_s, to the primary and secondary currents, I_p and I_s, using $P = IV$.

power in to primary coil = power out of secondary coil

$$I_p \times V_p = I_s \times V_s$$

It is important to remember that this equation assumes that no power is lost in the transformer. Worked Example 21.3 shows how to use this equation.

A school power pack has an output voltage of 9 V. It is plugged in to the 230 V mains supply. The power pack contains a transformer. The output current of the power pack is 3 A. Calculate the current supplied to the primary coil of the transformer in the power pack. Assume there are no energy losses in the transformer.

Step 1: Draw a transformer symbol and mark on the information from the question.

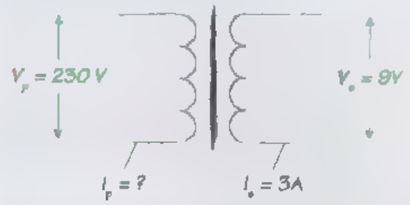


Figure 21.22: Transformer symbol with the known quantities.

Step 2: Write down the transformer power equation.
$I_p \times V_p = I_s \times V_s$

Step 3: Substitute values from the question.
$3\text{ A} \times 9\text{ V} = I_s \times 230\text{ V}$

Step 4: Rearrange and solve for I_s.

[illegible]

Answer

So the current supplied to the primary coil is 0.12 A.

In stepping down the voltage, the transformer has stepped up the current. If both had been stepped up we would be getting something for nothing – which in physics, is impossible!

Questions

14 A power station generates 230 000 W.

- **a** Calculate the current in the wires when the power is transmitted.
  - **i** at 230 V
  - **ii** at 23 000 V
- **b** Explain why it is better to transmit the electricity at a higher voltage.

15 The power supply to a factory is 100 kW. The wires have a resistance of 0.2 Ω.

- **a** Calculate the power loss in the cables when the voltage across the wires is 250 V.
- **b** Calculate the power loss when the voltage is stepped up to 12 500 V.

16 A transformer reduces the mains voltage from 240 V to 12 V for use in a school laboratory power pack. The current supplied by the power pack is 2 A. What current flows into the power pack? What assumption must you make in this calculation?

Look back through your work on the motor effect and electromagnetic induction. Are there any areas you need to work on? Ask yourself:

- Are you clear about what each effect is?
- Can you recall and understand the equations?
- Can you recall and use the relevant rules for finding directions of fields or currents?

Make revision cards with the key things you need to remember.

Power to the people

Figure 21.23: A town in Sweden.

In this Swedish town coal is mined then burned to generate electricity. The electricity is distributed to homes via the national grid.

Electrical power generation and distribution varies depending on where you live.

Your task is to research how electricity reaches you. Working in a small group you will research how electricity is generated and distributed in your country. You will work together to produce a large poster illustrating and explaining what you find. Your poster will have a lot of information, so plan carefully how the different parts will come together.

For example, you may decide to structure your poster around a diagram of the national grid, with information boxes for each stage.

You must include:

- information about the type of power stations and renewable resources which are in use
- a diagram of a generator and information about how it works and how it is used in power generation
- a diagram similar to Figure 21.16 showing how electricity is distributed
- information about the role of transformers in the system and the difference between step-up and step-down transformers
- reasons why the voltage of the supply has to be changed.

You could add:

- a pie chart showing the different energy resources used in your country
- a detailed explanation of how an a.c. generator works, including why the current generated is a.c. (not d.c.)
- details of the voltages at different parts of the grid, with calculations showing the transformers needed at each stage
- photographs from your local area showing pylons, substations, overhead cables and safety notices.

When there is relative movement between a conductor and a magnetic field, an e.m.f. is induced across the conductor.

The induced e.m.f. may cause an induced current to flow.

The e.m.f. induced in a coil of wire can be increased by:

- increasing the magnetic field strength
- increasing the number of turns on the coil
- increasing the speed of movement

The direction of the induced e.m.f. opposes the movement which causes it.

The direction of the induced e.m.f can be found using Fleming's right-hand rule

Direct current flows in one direction. Alternating current reverses direction repeatedly

The output of an a.c. generator depends on the position of the coil in relation to the magnetic field.

A transformer, consisting of a primary coil, a secondary coil and a soft iron core can be used to change alternating voltages.

A step-up transformer increases voltage, a step-down transformer decreases voltage.

The number of turns on transformer coils and the voltages across them can be calculated using the equation.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Transformers increase voltage for transmission by the national grid then reduce the voltage to a safer level for consumers.

a.c. in the primary core of a transformer creates a changing magnetic field which, in turn, induces a.c. in the secondary coil

When a transformer is assumed to be 100% efficient, the primary and secondary currents and voltages are related by the equation $I_p \times V_p = I_s \times V_s$.

The power losses in cables can be calculated using the equation $P = I^2R$

EXAM-STYLE QUESTIONS

1 Which one of these is not needed for electromagnetic induction? **[1]**

A a conductor
B movement
C a coil of wire
D a magnetic field

2 Which statement is true? **[1]**

A A step-down transformer decreases current.
B A step-up transformer increases voltage.
C A step-up transformer is used in a school laboratory power supply.
D A step-down transformer has more turns on the secondary coil than on the primary coil.

3 A student investigates the effect of moving a bar magnet into a coil.
She measures the current which flows in the coil when she moves the magnet.
Which change would increase the current? **[1]**

A using a stronger bar magnet
B moving the magnet in the opposite direction
C moving the coil instead of the magnet
D moving the coil from side to side as well as in and out of the magnet

5 a Which statement describes electromagnetic induction? [1]

A the production of an e.m.f across an electrical conductor when there is relative movement between the conductor and a magnetic field

B the production of an e.m.f across an electrical conductor when there is no movement between the conductor and a magnetic field

C the production of an e.m.f across an electrical conductor when there is relative movement between the conductor and an induced current

D the production of an e.m.f across an electrical conductor when there is no movement between the conductor and an induced current

b [illegible] an experiment to demonstrate electromagnetic induction using a horseshoe magnet, a piece of copper wire and a sensitive ammeter You may include a diagram in your answer. [3]

c [illegible] two factors which affect the size of the current induced in this experiment. [2]

[Total: 6]

6 a Draw a diagram of a step-up transformer and label the three essential parts of the transformer [4]

b A student connects the input of a step-up transformer to a battery He connects the output to a bulb, but it does not light [illegible] why. [1]

[Total: 5]

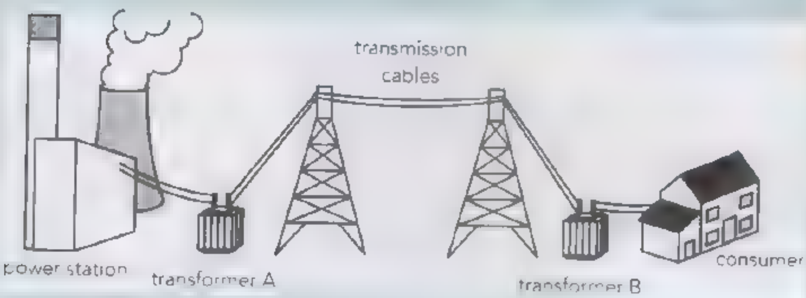
[illegible]: state the points of a topic, give characteristics and main features

state: express in clear terms

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

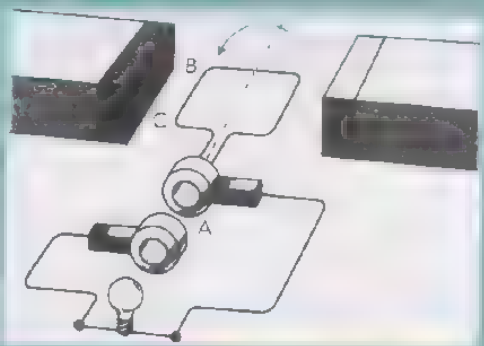
CONTINUED

7 a Transformers are used in the national grid to change the voltage of the supply. For transformers A and B, state whether the transformer is step-up or step-down, and explain why the voltage change is necessary. [4]

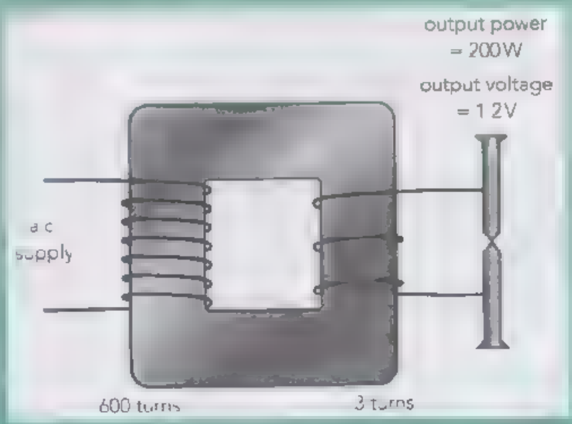


b A transformer in the national grid has 800 turns on the primary coil and 16 000 on the secondary. The primary voltage is 25 kV. [illegible] the secondary voltage. [2]

[Total: 6]



calculate: work out from given facts, figures or information



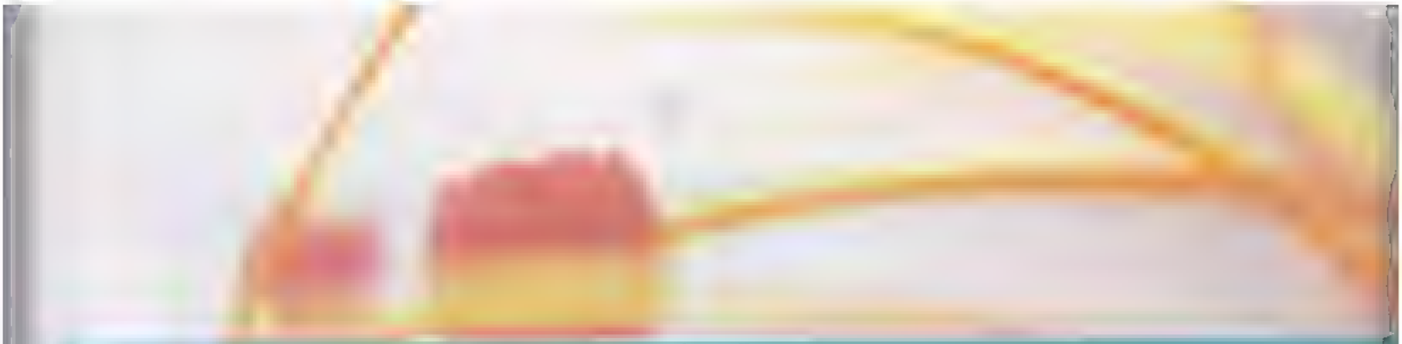
Total

give: produce an answer from a given source or recall / memory

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
State that an e.m.f. is induced when there is relative movement between a conductor and a magnetic field, and describe an experiment to demonstrate this.	21.1			
List the ways in which the induced e.m.f. can be increased.	21.1			
State that the induced e.m.f. opposes the change which causes it.	21.1			
Use Fleming's right-hand rule to find the direction of the induced current.	21.1			
Describe the structure and operation of an a.c. generator.	21.1			
Sketch a graph of voltage against time for an a.c. generator. State what position the coil must be in for the peaks, troughs and zeros on the graph.	21.1			
List the three essential parts of a transformer.	21.2			
Describe the difference between a step-up and a step-down transformer, by comparing their primary and secondary coils.	21.2			
Recall and use the equation $\frac{V_p}{V_s} = \frac{N_p}{N_s}$	21.2			
Describe how and why transformers are used in high voltage transmission.	21.2			
Explain how a transformer works.	21.3			
Recall and use the equation $I_p \times V_p = I_s \times V_s$.	21.3			
Recall and use the equation $P = I^2R$.	21.3			



> Chapter 22

The nuclear atom

IN THIS CHAPTER YOU WILL

- describe the structure of the atom
- describe the alpha scattering experiment which provides evidence for the nuclear atom
- name and state the mass and charge of the particles in the nucleus
- represent nuclei in the form $^A_Z X$
- explain what isotopes are
- [illegible]

With a partner, spend two minutes making notes on what you know about atoms. Include a sketch of an atom.

Now discuss these statements and decide which are true and which are false:

- Atoms are the smallest particles there are
- There are 92 different types of atom.
- Most of the mass of an atom is in the nucleus.
- Atoms have no charge.

Figure 22.1a: New understanding of the structure of the atom lead to the development of the nuclear bomb **b.** Lise Meitner was the first person to describe nuclear fission but did not share in the Nobel prize awarded for this discovery.

The early 20th century was an exciting time to be a physicist. The idea of atoms had been around since Democritus in ancient Greece, but now huge strides were being made in understanding how atoms were made up. Ernest Rutherford had described a new model of the atom, containing a tiny, dense nucleus and the particles in the nucleus were identified.

These discoveries were being made alongside the rise of fascism in Europe which lead to the Second World War. German physicist Otto Hahn split a uranium nucleus and found barium in the debris of his experiment. Lise Meitner, a Jewish colleague of Hahn, working in exile in Sweden, explained the process and called it nuclear fission. Hahn was later awarded the Nobel prize for this discovery. Nuclear fission releases a huge amount of energy and the Hungarian scientist, Leo Szilard, also working in exile, realised that this could be used to make a bomb. The fear was that Nazi scientists would create this bomb, allowing them to win the war.

Szilard enlisted the help of Einstein in writing to the US president to persuade him of the necessity of developing the bomb before the Nazis did. After the bombing of Pearl Harbor the USA joined the war. Within a year the Manhattan Project successfully produced the chain reaction needed for the bomb. In 1945 bombs were dropped causing thousands of deaths in Hiroshima and Nagasaki in Japan.

J. Robert Oppenheimer, one of the Manhattan Project team who developed the bomb, described it using words from the Bhagavad Gita, 'Now I am become Death, the destroyer of worlds'. After the end of the Second World War, Oppenheimer campaigned for international cooperation to limit the proliferation of nuclear arms.

There are now about 27 000 nuclear bombs in the world.

Discussion questions

1. To what extent are scientists responsible for the ways in which their discoveries are used?
2. Should the nuclear physicists have destroyed their research when they realised how destructive it could be?

22.1 Atomic structure

At one time, physics textbooks would have said that atoms are very tiny, too tiny ever to be seen. Certainly, a single atom is too small to be seen using a conventional light microscope. But technology now allows us to see into the atom. There is more than one kind of microscope that can be used to show individual atoms. Figure 22.2 shows a photograph made using a scanning tunnelling microscope. The picture shows silicon atoms on the surface of a crystal of silicon (the material that transistors and computer chips are made from). The diamond shape shows a group of 12 atoms. The whole crystal is made up of vast numbers of groups of atoms like this.

Figure 22.2: Individual silicon atoms (bright spots, artificially coloured by a computer) on the surface of a silicon crystal, observed using a scanning tunnelling microscope. The diamond shape (which has been drawn on the image) indicates the basic repeating pattern that makes up the crystal structure of silicon. In this photograph, the silicon atoms are magnified 100 million times. (A good light microscope can only magnify by about 1000 times.) Roughly speaking, 4 000 000 000 atoms would fit into a length of 1 metre.

In 1909, Ernest Rutherford and his colleagues discovered that every atom has a tiny central nucleus. This gave rise to the 'solar system' model of the atom shown in Figure 22.3. In this model, the negatively charged electrons orbit the positively charged nucleus. The electrons are attracted to the nucleus (because of its opposite charge), but their speed prevents them from falling into it.

Figure 22.3: The nuclear model of the atom. Six electrons are illustrated orbiting a nucleus made up of six protons and six neutrons

Forming ions

An atom has equal amounts of positive and negative charge so is neutral overall. Electrons can be gained or lost by atoms relatively easily, for example by rubbing an insulator as we saw in Chapter 17. This leads to the formation of ions in a process called **ionisation**. An atom which gains an electron has more negative than positive charge and so becomes a negative ion. An atom which loses an electron is left with more positive than negative charge and so becomes a positive ion.

ionisation: when a particle (atom or molecule) becomes electrically charged by losing or gaining electrons

Discovering the nucleus

Electrons were discovered in 1896 by the English physicist J. J. Thomson. He realised that electrons were much smaller and lighter than atoms. (We now know that the mass of an electron is about $\frac{1}{1836}$ of the mass of a hydrogen atom.) He guessed, correctly, that electrons were part of atoms.

Other scientists argued that, since electrons had negative charge, there must be other particles in an atom with an equal amount of positive charge, so that an atom has no overall charge – (it is neutral). Since electrons have very little mass, the positive charge must also account for most of the mass of the atom. Figure 22.4 shows a model that illustrates this. The atom is formed from a sphere of positively charged matter with tiny, negatively charged electrons embedded in it. This is called the **plum pudding model**. In this model, the electrons are the negatively charged plums in a positively charged pudding. You can see that this is a different model from the solar system model we described earlier (Figure 22.3).

Figure 22.4a: A plum pudding is a cake with fruit dotted through it. **b:** In Thomson's model, the negatively charged electrons are the plums stuck in a positively charged pudding

KEY WORDS

plum pudding model: a disproved model of the atom which imagined it to consist of a positive 'pudding' with electrons dotted through it

alpha particle (α-particle): a particle made up of two protons and two neutrons; it is emitted by an atomic nucleus during radioactive decay

So why do we no longer think that atoms are like plum puddings? The answer comes from an experiment carried out by the New Zealander, Ernest Rutherford, and his colleagues, Hans Geiger and Ernest Marsden, about ten years after Thomson's discovery of the electron.

They fired tiny particles called **alpha particles** at a very thin piece of gold foil. Alpha particles are tiny, but an alpha particle has almost 8000 times as much mass as an electron, and they were moving fast (you will learn more about alpha particles in chapter 23). They used gold as it is easy to get gold foil which is only a few atoms thick. Their calculations suggested this was a bit like firing bullets at plum puddings. They predicted that the alpha particles would pass straight through the gold.

Geiger and Marsden found that most of the alpha particles passed straight through the gold foil, scarcely deflected. However, a few bounced back towards the source of the radiation. It was as if there was something very hard in the gold foil, like a ball-bearing buried inside the plum pudding. What was going on?

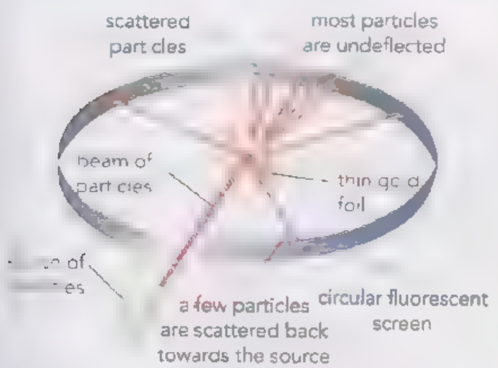


Figure 22.5: The experiment to show alpha particle scattering by gold foil. Alpha particles from the source strike the foil. Most pass straight through, and some are deflected a bit. A few, about one in 8000, are scattered back towards the source. The experiment is performed in a vacuum as air would absorb the alpha particles.

Rutherford realised that the answer was to do with electric charge. Alpha particles are positively charged. If they are repelled back from the gold foil, it must be by another positive charge. If only a few were repelled, it was because the positive charge of the gold atoms was concentrated in a tiny space within each atom. Most alpha particles passed straight through because they never went near this concentration of charge (see Figure 22.6). This tiny core of concentrated positive charge, at the heart of every atom, is what we now call the atom's **nucleus**.

Rutherford concluded that:

- most of the mass of an atom is concentrated in the central nucleus
- the nucleus is positively charged
- the nucleus is tiny compared to the atom; an atom is mainly empty space.

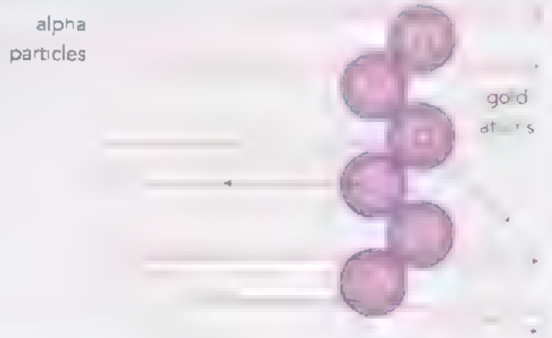


Figure 22.6: Most alpha particles pass straight through the gold foil because they do not pass close to the atomic nucleus. The closer they are to the nucleus, the more they are deflected or scattered. Only those which head straight to the nucleus are reflected straight back.

In later years, Rutherford often spoke of the surprising results of the alpha scattering experiment. He said:

It was quite the most incredible event that ever happened to me in my life. It was as if you fired a fifteen-inch artillery shell at a piece of tissue paper and it came back and hit you.

KEY WORD

nucleus: small, dense, positively charged region at the centre of an atom

A sense of scale

Rutherford was able to analyse the results from Geiger and Marsden's experiment to work out just how big the nucleus of a gold atom was. An atom is small (about 10^{-10} metres across) but its nucleus is very much smaller (about 10^{-15} metres in diameter). The electrons travel around the nucleus. They are even tinier than the nucleus. And the rest of the atom is simply empty space.

It is hard to imagine these relative sizes. Try picturing a glass marble about 1 cm in diameter placed at the centre of a football pitch, to represent the nucleus of an atom. Then the electrons are like tiny grains of dust, orbiting the nucleus at different distances, right out to the edge of the football ground.

It is even harder to imagine, when you stub your toe on a rock, that the atoms of the rock (and your toe) are almost entirely empty space!

A successful model

Rutherford's model of the atom was soon accepted by other scientists. It gave a clear explanation of the alpha particle scattering experiment, and further tests with other metals confirmed Rutherford's ideas. It clearly showed that the plum pudding model was wrong.

Rutherford's model also allowed scientists to think about other questions. Chemists wanted to know how atoms bonded together. Physicists wanted to understand why some atoms are unstable and emit radiation, and how X-rays are produced. These are all questions to which we now have good answers, and Rutherford's discovery of the atomic nucleus did a lot to help answer them.

Today, scientists have rather different ideas about atoms. They want to calculate many different quantities, and so models of the atom are much more mathematical. Quantum theory, developed not long after Rutherford's work, made the atom seem like a much fuzzier thing, not a collection of little spheres orbiting each other. However, the important thing about a model is that it should help us to understand things better, and help us to make new predictions. Rutherford's model of the nuclear atom has certainly done that.

ACTIVITY 22.1

Nuclear news

Imagine you are a science reporter. You have been sent to interview Rutherford following the alpha particle scattering experiment. Think about how you could report this in a way that conveys Rutherford's amazement at what his team discovered. Prepare either a newspaper report or a videoed interview (clearly this wouldn't have been an option in 1909 when the experiment took place!)

Remember that the audience are not scientists, so you will need to introduce the idea of atoms and explain what scientists before Rutherford thought.

Questions

1 In the plum pudding model of the atom
   a what are the plums?
   b what is the pudding?
2 In the alpha particle scattering experiment, explain what happened to alpha particles
   a heading directly towards a gold nucleus
   b passing close to a gold nucleus
   c passing through the empty space between nuclei.
3 How did this experiment prove that the nucleus must be very small?
4 In the solar system model of the atom, what force holds the electrons in their orbits around the nucleus?

22.2 Protons, neutrons and electrons

We now know that the atomic nucleus is made up of two types of particle, **protons** and **neutrons**. The protons carry the positive charge of the nucleus, while the neutrons are neutral. Negatively charged electrons orbit the positively charged nucleus. Protons and neutrons have similar masses, and they account for most of the mass of the atom because electrons are so light. Together, protons and neutrons are known as **nucleons**.

Table 22.1 summarises information about the masses and charges of the three sub-atomic particles. The columns headed **Relative charge** and **Relative mass** give the charge and mass of each particle compared to that of a proton. It is much easier to remember these values, rather than the actual values in coulombs (C) and kilograms (kg).

[illegible]

proton: a positively charged particle found in the atomic nucleus

neutron: an uncharged particle found in the atomic nucleus

nucleon: a particle found in the atomic nucleus; a proton or a neutron

relative charge: the charge of a particle relative to the charge of a proton

relative mass: the mass of a particle relative to the mass of a proton

Atoms and elements

Once the particles that make up atoms were identified, it was much easier to understand the Periodic Table of the elements (Figure 22.7). This shows the elements in order, starting with the lightest (hydrogen, then helium) and working up to the heaviest. In fact, it is not the masses of the atoms that determine the order in which they appear, but the number of protons in the nucleus of each atom. Every atom of hydrogen has one proton in its nucleus, so hydrogen is element number 1. Every helium atom has two protons, so helium is element number 2, and so on.

Particle	Position	Charge / C	Relative charge	Mass / kg	Relative mass
proton	in nucleus	$+1.6\times10^{-19}$	+1	1.67×10^{-27}	1
neutron	in nucleus	0	0	1.67×10^{-27}	1
electron	orbiting nucleus	-1.6×10^{-19}	−1	9.11×10^{-31}	$\frac{1}{1836}$ (practically zero)

Table 22.1 Charges and masses of the three sub-atomic particles.

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La to Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac to Lr															

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
89 Ac	90 Th	91 Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 22.7: The Periodic Table of the elements is a way of organising what we know about the different elements, based on atomic structures.

Each element has its own symbol, consisting of one or two letters, such as H for hydrogen, and He for helium. Sometimes, the symbol for an atom may be written with two numbers in front of it, one above the other, such as:

${}^{4}_{2}\text{He}$

This represents an atom of helium. The bottom number tells us that there are two protons in the nucleus of an atom of helium, and the top number tells us that there is a total of four nucleons in the nucleus of an atom of helium. From this, it is simple to work out that there must be two neutrons in the nucleus.

We can write the general symbol for an element (X) with its **proton number** (Z), which is the number of protons in the nucleus, and **nucleon number** (A), which is the number of nucleons (protons and neutron) in the nucleus, as follows:

${}^{A}_{Z}\text{X}$

Z is proton number (also known as the atomic number) and A is nucleon number (also known as the mass number). This is known as nuclide notation.

A neutral atom of element X will also have Z electrons orbiting the nucleus.

proton number (Z): (or atomic number) the number of protons in an atomic nucleus

nucleon number (A): (or mass number) the number of nucleons (protons and neutrons) in an atomic nucleus

What strategies have you found useful in remembering the properties of each of the subatomic particles and the definitions of nucleon and proton numbers? Share your strategies with a partner.

Questions

5 Copy and complete these sentences:

An atom has a tiny, dense ______. This contains positively charged ______ and neutral ______. These two particles have approximately the same ______.

A nucleus can be described by two numbers: the proton number, and the nucleon number which is the total number of ______ and ______ in the nucleus.

6 Copy and complete Table 22.2

Subatomic particle	Position	Relative charge	Relative mass
proton			1
electron		−1	
	in the nucleus		

Table 22.2

7 A particular neutral atom of boron is represented by ${}^{12}_{5}\text{B}$

a What is its proton number?

b What is its nucleon number?

c Write down the numbers of protons, neutrons and electrons it contains.

8 A cobalt atom contains 33 neutrons.

a Use the periodic table to find its proton number

b Write down an expression in the form ${}^{A}_{Z}\text{X}$ to represent the cobalt nucleus.

9 How many times greater is the mass of a proton than the mass of an electron?

Elements and isotopes

It is the proton number, Z, that tells us which element an atom belongs to. For example, a small atom with just two protons in its nucleus ($Z = 2$) is a helium atom. A much bigger atom with 92 protons in its nucleus is a uranium atom, because uranium is element 92.

From Z and A you can work out a third number, the **neutron number** (N), which is the number of neutrons in the nucleus.

proton number + neutron number = nucleon number

$Z + N = A$

neutron number (N): number of neutrons in the nucleus of an atom

What can you deduce about the atom whose nucleus can be represented by $^{14}_{6}C$?

Step 1: Look at the atomic symbol.

The symbol C tells us it is a carbon nucleus.

Step 2: Identify the number of protons:

$Z = 6$

Step 3: Identify the number of electrons.

It is a neutral atom, so it has the same number of protons as electrons = 6.

Step 4: Calculate the number of neutrons:

$N = A - Z = 14 - 6 = 8$

Answer

$^{14}_{6}C$ is a carbon nucleus with six protons, six electrons and eight neutrons.

The atoms of all elements exist in more than one form For example, Figure 22.8 shows three types of hydrogen atom. Each has just one proton in its nucleus, but they have different numbers of neutrons (0, 1 and 2). This means that they are described as different **isotopes** of hydrogen.

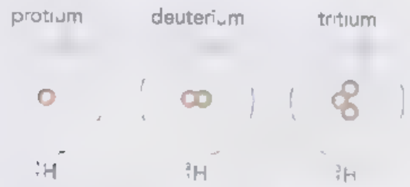


Figure 22.8: Hydrogen exists in three different forms known as isotopes. All three have the same proton number

- The different isotopes of an element all have the same chemical properties, but those with a greater number of neutrons are heavier.
- The different isotopes of an element all have the same number of protons but different numbers of neutrons in their nuclei

isotope: isotopes of an element have the same proton number but different nucleon numbers

Table 22.3 shows atoms of two isotopes of helium, ^4_2He (the most common isotope) and ^3_2He (a lighter and much rarer isotope). Each ^3_2He has two protons in the nucleus and two electrons orbiting it, but the lighter isotope has only one neutron. These isotopes are referred to as helium-4 and helium-3.

Symbol for isotope	Proton number Z	Neutron number N	Nucleon number A
^4_2He	2	2	4
^3_2He	2	1	3

Table 22.3: Isotopes of helium.

Table 22.4 shows two isotopes of uranium Uranium-238 is the most common isotope. Uranium-238 has three more neutrons than uranium-235, but the same number of protons. Uranium-235 is used in nuclear power stations as its nuclei can be split to release a huge amount of energy.

Symbol for isotope	Proton number Z	Neutron number N	Nucleon number A
$^{235}_{92}U$	92	143	235
$^{238}_{92}U$	92	146	238

Table 22.4: Isotopes of uranium

Isotopes at work

All elements have isotopes, some as many as 36. For most chemical elements, at least one isotope is stable Other isotopes are often unstable. This means that the nucleus is likely to give out radioactivity in order to become stable. You will learn about radioactive decay in Chapter 23.

Questions

10 Carbon exists in two forms $^{12}_{6}C$ and $^{14}_{6}C$.

a Write down the number of protons, neutrons and electrons in each

b Copy and complete these sentences:

$^{12}_{6}C$ and $^{14}_{6}C$ are two ______ of carbon.

They have the same ______ number, but different ______ numbers.

Both have the same ______ properties.

11 Table 22.5 lists the proton and nucleon numbers of six different nuclei.

- **a** Copy and complete the table by filling in the empty spaces.
- **b** Which three nuclei are isotopes of one element?
- **c** Which two nuclei are isotopes of another element?
- **d** Use the Periodic Table (Figure 22.7) to identify the three elements in Table 22.5.

Nucleus	Proton number Z	Neutron number N	Nucleon number A
Nu-1	6	6	
Nu-2		6	13
Nu-3	7		14
Nu-4		8	14
Nu-5		6	11
Nu-6		7	13

Table 22.5 Proton and nucleon numbers of nuclei

Charge and mass of nuclei

The charge on a nucleus is equal to the number of protons as each proton has a relative charge of +1. So all three isotopes of hydrogen have a charge of +1 as all contain just one proton.

The mass of a nucleus is equal to the mass of the nucleons as both protons and neutrons have a relative mass of one. Each of the hydrogen isotopes has a different mass. Protium has a mass of one, deuterium has a mass of two and tritium has a mass of three.

Question

12 Write down the mass and charge of the nuclei of the helium and uranium isotopes shown in Tables 22.3 and 22.4.

Nuclear fission and fusion

In Chapter 7 you learnt about the use of nuclear fuels. These produce energy by splitting nuclei which is a process known as nuclear fission. Figure 22.9 shows a fission reaction in which a uranium-235 nucleus is hit by a neutron. The extra neutron causes it to become unstable and it splits, making two new nuclei and three extra neutrons. A large amount of energy is also released. These neutrons can then split, leading to a chain reaction.

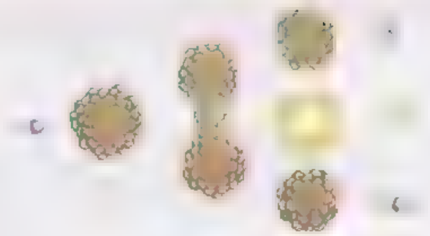


Figure 22.9: A uranium-235 nucleus being split to make barium and krypton nuclei, three more neutrons and a lot of energy

This reaction can be represented by a balanced nuclear equation

$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Ba + ^{141}_{56}Kr + 3^{1}_{0}n$ + energy

Both the proton numbers and the nucleon numbers must be equal on each side of the equation:

Proton number: $92 + 0 = 36 + 56 + 3(0)$
$92 = 92$ ✓

Nucleon number: $235 + 1 = 92 + 141 + 3(1)$
$236 = 236$ ✓

Nuclear fusion produces even more energy than nuclear fission. Fusion is when two nuclei join together to form a larger nucleus. This can only happen at extremely high temperatures. Fusion is the process by which stars produce heat and light. The equation below shows one of the fusion reactions which occurs in the Sun. You can see that the proton and nucleon numbers balance.

$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$

Something for nothing?

As you know, energy cannot be created or destroyed. So, where does the huge amount of energy released in fission and fusion come from? To answer this we need one of the most famous equations in physics:

$E = mc^2$

The total mass of the particles before a fission or fusion reaction is found to be slightly more than the total mass after the reaction. The mass which is lost is converted to energy, and Einstein's equation allows us to calculate the amount of energy released:

energy released (E) = mass lost (m) × the speed of light squared (c^2)

The speed of light squared is a huge number, so even a very small loss of mass will produce a large amount

A brief history of particle physics

Throughout history mankind has tried to explain the world around us and what it is made of. This has led to an understanding of atoms, then their constituent protons, neutrons and electrons. In this chapter we have covered part of this story, but there have been many scientists making discoveries and often receiving Nobel prizes for their work. And the story is not complete. In 2012, scientists at CERN detected the Higgs boson. It is a particle which had been predicted theoretically and which helps in our understanding of gravity.

a

Figure 22.10a: Ernest Rutherford (shown here in his laboratory at Manchester University) **b:** The Large Hadron Collider (LHC) at CERN in Switzerland. The LHC is so big that scientists cycle from one part of an experiment to another

Produce a timeline or presentation showing the main developments in particle physics from ancient world thought to present day investigations using the Large Hadron Collider.

You could investigate the contributions of:

- the Jains in Ancient India
- ancient Greeks such as Democritus and Leucippus
- John Dalton
- J. J. Thomson
- Ernest Rutherford, Hans Geiger and Ernest Marsden
- James Chadwick
- Murray Gell-Mann
- Francois Englert and Peter Higgs

You should include diagrams to explain experiments and models of the atom. Try to include as many of the key words from this chapter as you can.

Your presentation should focus on the way in which ideas follow on from each other. It should inspire people with the knowledge that there is still a lot to be discovered by the physicists of tomorrow.

PEER ASSESSMENT

Give feedback to another group. Write comments on these points:

- Does the presentation make it clear what each scientist contributed to the story?
- Are the experiments described clearly?
- Do you feel it gives the reader/viewer a sense of scientists building on the work of those who went before them?

The atom consists of a tiny positive nucleus surrounded by mainly empty space with negative electrons [illegible]
Positive or negative ions are formed when an atom loses or gains electrons.
The nucleus contains two types of nucleons: positively charged protons and neutral neutrons.
Rutherford's alpha particle scattering experiment provided evidence to support the nuclear model of the atom.
Protons and neutrons have approximately the same mass. This is nearly 2000 times the mass of an elect[illegible]
Protons and electrons have equal but opposite charge.
A nucleus can be described using the notation $^{A}_{Z}X$, where X is the chemical symbol, Z the number of protons and A the number of nucleons.
Isotopes are nuclei of the same element which have the same proton number but different nucleon numbers.
Nuclear fission is the splitting of a large nucleus, which releases a lot of energy.
Nuclear fusion is joining together of small nuclei, which releases even more energy than fission.
Nuclear fission and fusion can be described using nuclear equations.

EXAM-STYLE QUESTIONS

1 Which row correctly gives the relative charge of a proton, neutron and electron? [1]

	Proton	Neutron	Electron
A	1	0	1
B	1	1	1
C	−1	0	1
D	1	0	−1

2 A nucleus is represented by the notation $^{193}_{82}Pb$. What particles does it contain? [1]

- **A** 82 protons and 193 neutrons
- **B** 82 protons, 82 electrons and 111 neutrons
- **C** 82 neutrons and 111 protons
- **D** 82 protons and 111 neutrons

3 An element has two isotopes. What is different for the two isotopes? [1]

- **A** the number of protons
- **B** the chemical symbol
- **C** the number of neutrons
- **D** the chemical properties of the isotope

4 **a** Name the two types of particles found in an atom's nucleus. [2]

b State the name given to the total number of particles in a nucleus. [1]

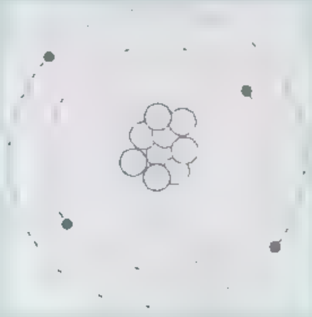
c Describe what happens to the charge on an atom when it gains an electron. [2]

[Total: 5]

state: express in clear terms

describe: state the points of a topic / give characteristics and main features

5 The diagram shows a neutral beryllium atom



a How many electrons does the atom have? [1]

b How many protons does it have? [1]

c What is its nucleon number? [1]

d How many neutrons does it have? [1]

e Copy and complete this nuclear notation to represent the beryllium nucleus:

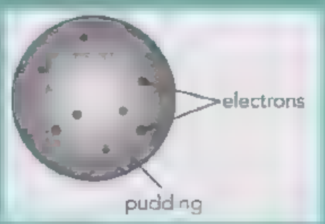
$^{\square}_{\square}\mathrm{Be}$ [1]

f A radioactive isotope of beryllium is known as beryllium-11. How many protons, neutrons and electrons does an atom of this isotope contain? [3]

g Write down the nuclear notation for beryllium-11. [2]

[Total: 10]

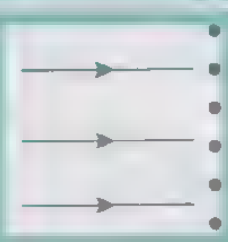
[illegible]



[illegible]

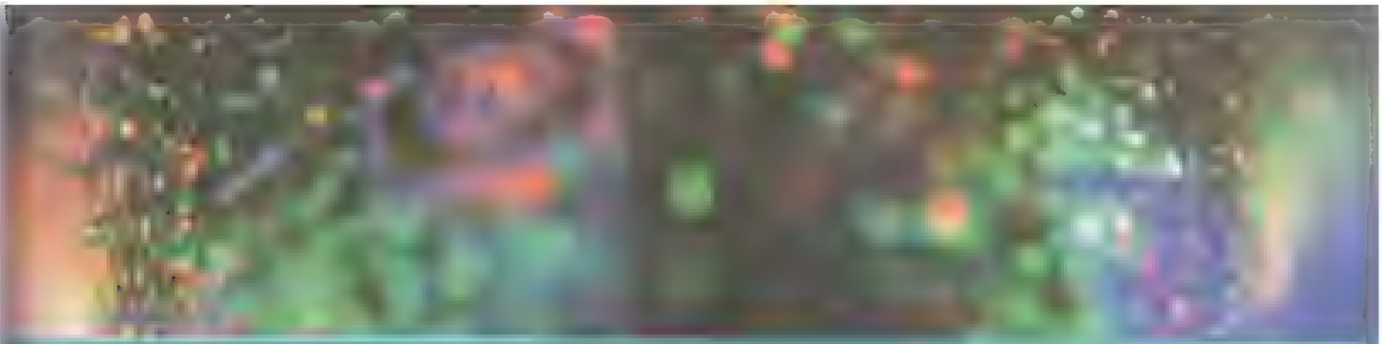
[illegible] d Marsden carried out an experiment which showed the plum [illegible] nly a few atoms thick. The diagram below shows three alpha parti [illegible]

CONTINU



After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

Describe the structure of the atom	22.1			
Describe how ions are formed	22.1			
Describe Rutherford's alpha scattering experiment and its conclusions.	22.1			
Name the particles in the nucleus and state their mass and charge	22.2			
Define proton number Z	22.2			
Define nucleon number A	22.2			
Describe nuclei using the notation ${}^{A}_{Z}X$	22.2			
Describe the similarities and differences between two isotopes of an element	22.2			
Describe the processes of nuclear fission and fusion.	22.2			
State what the proton and nucleon numbers tell us about the charge and mass of a nucleus.	22.2			



> Chapter 23

Radioactivity

IN THIS CHAPTER YOU WILL:

- explain the term 'background radiation' and list some of its sources
- describe how ionising nuclear radiation is measured
- describe the nature and behaviour of alpha, beta and gamma radiation
- [illegible]
- describe radioactive decay
- [illegible]
- define and calculate radioactive half-life
- consider the safety issues around ionising nuclear radiation.

In this chapter we will look at the radiation emitted from the nuclei of unstable isotopes, which can cause ionisation. This will include high frequency electromagnetic radiation.

The sentences above include a lot of key words you have met elsewhere in this book. Write down as many as you can in a table. Try to define each word from memory before referring to your notes or to the glossary at the back of the book. Research shows that trying to recall information like this is a great way of getting it to stick in your mind.

Key word	Definition from memory	Definition from notes or glossary

LECTION

Did you remember the key parts of the definitions? How can you help yourself to learn important definitions?

Consider making revision cards and regularly checking what you know. Find out about mobile phone apps which help you do this.

Radioactivity was first discovered in 1896. Soon afterwards, in 1898, Marie Curie discovered radium which was found to be useful in treating cancer. It was assumed that these emissions which could cure cancer, must be healthy. Radium was used to treat any conditions where the patient seemed to need more energy, from anaemia to impotence. An industry developed selling products such as radioactive water, toothpaste and face creams to give you a 'healthy' glow. Figure 23.1 shows an advert for such a cream.

Radium was used in paint which converted the radiation it emitted into light. The process is called luminescence. This was used to make watch and clock faces visible in the dark.

The radium was painted on to these watches by young women in factories. These jobs were popular as radium was a glamorous, expensive product and the work was much cleaner than other factory work. The women used camel hair brushes to apply the radioactive paint. They were told to squeeze these brushes between their lips as they worked to keep a fine point on the brush. These instructions came from factory owners who knew that research was beginning to show that radium was a dangerous substance and so limited their own exposure to it. Some workers questioned whether the radium was safe and were reassured that they were not at risk.

Figure 23.1: The name Tho-Radia refers to the radioactive isotopes of thorium and radium used in this face cream.

CONTINUED

Figure 23.2: The radium girls painted luminous radioactive paint on clock and watch faces.

Radium is chemically similar to calcium and the radium replaced calcium in the bones of the women, weakening and damaging their bones. They experienced pain and many – probably thousands – developed bone and other cancers which were often fatal. When the women began to die, some factory owners tried to blame their deaths on a virus, or on syphilis.

Eventually the women won a court case in 1928 and the survivors received compensation, though the companies appealed and it was only in 1939 that the case was finally won. Luminous watches were still sold until the 1960s, though the painting techniques were changed.

Discussion questions

1 Why did the factory owners not inform the workers about the dangers of working with radium?

2 Do you think this situation could happen today? Consider ways in which laws and access to information may have made this less likely.

23.1 Radioactivity all around us

We need to distinguish between two things: **radioactive substances** and the **radiation** that they give out. Many naturally occurring substances are radioactive. Usually the radiation in these substances is not very concentrated, so they do not cause a problem. There are two ways in which radioactive substances can cause us problems:

- If a radioactive substance gets inside us, its radiation can harm us. We say that we have been **contaminated**.
- If the radiation a radioactive substance produces hits our bodies, we receive a dose of radiation. We have been **irradiated**.

In fact, we are exposed to low levels of radiation all the time – this is known as **background radiation**. In addition, we may be exposed to radiation from artificial sources, such as the radiation we receive if we have a medical X-ray.

Figure 23.3 shows the different sources that contribute to the average dose of radiation received by people across the world. It is divided into natural background radiation (about 85%) and radiation from artificial sources (about 15%). We will look at these different sources in turn.

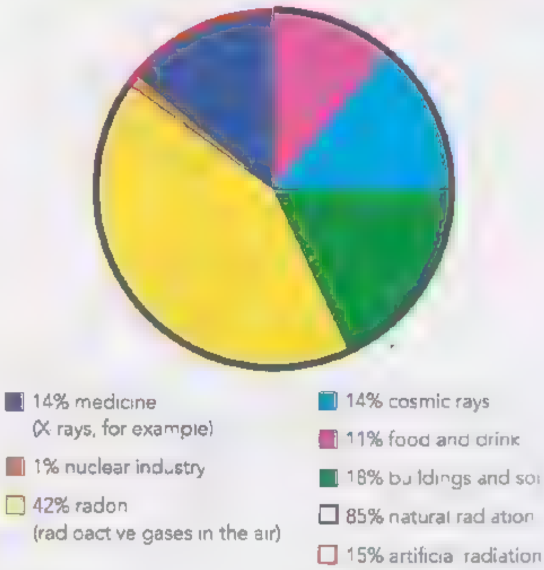


Figure 23.3: This pie chart shows the different sources of radiation and how they contribute to the average dose of radiation received each year by an individual. Only about 15% comes from non-natural sources.

Sources of natural background radiation

The air is radioactive. It contains a radioactive gas called radon, which seeps up to the Earth's surface from radioactive uranium rocks underground. Because we breathe in air all the time, we are exposed to radiation from this substance. This contributes about half of our annual exposure. (This varies widely from country to country, and from one part of a country to another, depending on how much uranium there is in the underlying rocks.)

The ground contains radioactive substances. We use materials from the ground to build our houses, so we are exposed to radiation from these.

Our food and drink is also slightly radioactive. Living things grow by taking in materials from the air and the ground. Some of these materials are radioactive so the plants which feed into our food chains will also be slightly radioactive.

Finally, radiation reaches us from space in the form of cosmic rays. Some of this radiation comes from the Sun, some from further out in space. Most cosmic rays are stopped by the Earth's atmosphere. If you live up a mountain, you will be exposed to more radiation from this source.

Because natural background radiation is around us all the time, we have to take account of it in experiments. It may be necessary to measure the background level and then to subtract it from experimental measurements.

Sources of artificial background radiation

Most radiation from artificial sources comes from medical sources. This includes the use of X-rays and gamma rays for seeing inside the body, and the use of radiation for destroying cancer cells. There is always a danger that exposure to such radiation may trigger cancer. Medical physicists are always working to reduce the levels of radiation used in medical procedures. Overall, many more lives are saved than lost through this beneficial use of radiation.

Today, most nuclear weapons testing is done underground. In the past, bombs were detonated on land or in the air, and this contributed much more to the radiation dose received by people around the world.

When you fly in an aircraft, you are high in the atmosphere. You are exposed to more cosmic rays. This is not a serious problem for the occasional flier, but aircraft crews have to keep a check on their exposure.

Many people, such as medical radiographers and staff in a nuclear power station, work with radiation. Overall, a power station does not add much to the national average dose, but for individuals who work there it can increase their dose by up to 10%.

Finally, small amounts of radioactive substances escape from the nuclear industry, which processes uranium for use as the fuel in nuclear power stations and handles the highly radioactive spent fuel after it has been used.

Detecting radiation

Radiation can be measured using a Geiger counter. This consists of a detector called a Geiger-Müller tube which detects radiation, connected to a counter. The counter records the rate at which radiation is detected. This is known as the **count rate** and it is measured in counts per second (count/s) or counts per minute (count/min)

Figure 23.4: Using a Geiger counter to monitor radiation levels in crops

radioactive substance: a substance that decays by emitting radiation from its atomic nuclei

radiation: energy spreading out from a source carried by particles or waves

contaminated: when an object has acquired some unwanted radioactive substance

irradiated: when an object has been exposed to radiation

background radiation: the radiation from the environment to which we are exposed all the time

count rate: the number of decaying radioactive atoms detected each second (or minute, or hour)

Questions

1 Describe what is meant by the term 'background radiation'.

2 Name three sources of natural background radiation and three sources of artificial background radiation.

3 Which type of natural background radiation are airline crews exposed to more than most people?

23.2 Radioactive decay

Not all nuclei give out radiation. Some nuclei are unstable and give out radiation in order to become more stable. This process is known as **radioactive decay**.

If you listen to the clicks or beeps of a Geiger counter, you may notice that it is impossible to predict when the next sound will come. This is because radioactive decay is a **random process**. Radioactive substances contain unstable nuclei which will decay spontaneously. We cannot predict which nucleus will decay next or when this will happen. The direction in which the radiation will be emitted is also random. Radioactive decay is not affected by external factors such as temperature.

Why are some nuclei unstable?

Radiation is emitted by the nucleus of an atom which is unstable. Many elements have isotopes which are radioactive because their nuclei are unstable. For some isotopes this is because the nucleus is too heavy. Other isotopes are unstable because they have too many neutrons. An unstable nucleus emits radiation in order to become more stable.

Fortunately, most of the atoms around us have stable nuclei. When the Earth formed, about 4500 million years ago, there were many more radioactive atoms around. This means that the level of background radiation used to be much higher than it is today. However, most radioactive atoms have decayed to become stable.

Three types of radiation

There are three types of radiation emitted by radioactive substances (Table 23.1). These are named after the first three letters of the Greek alphabet, alpha (α), beta (β) and gamma (γ). Alpha and beta are particles; gamma is a form of electromagnetic radiation (see Chapter 15).

Name	Symbol	Made of	Charge
alpha	α	2 protons + 2 neutrons	positive
beta	β	an electron	negative
gamma	γ	electromagnetic radiation	neutral

Table 23.1: Three types of radiation produced by naturally occurring radioactive substances

- An alpha particle (α-particle) is made up of two protons and two neutrons. (This is the same as the nucleus of a helium atom.) Because it contains protons, it is positively charged.
- A **beta particle (β-particle)** is an electron. It is not one of the electrons that orbit the nucleus – it comes from *inside the nucleus*. It is negatively charged, and its mass is much less than that of an alpha particle.
- A **gamma ray (γ-ray)** is a form of electromagnetic radiation with a very short wavelength and high frequency. It is similar to an X-ray, but has more energy.

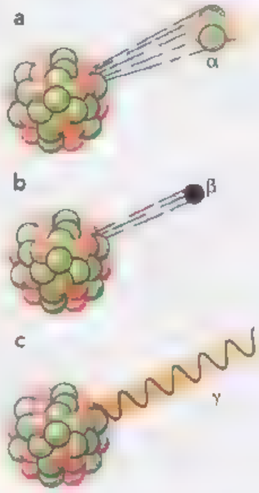


Figure 23.5a: Alpha emission **b:** Beta emission **c:** Gamma emission

radioactive decay: the emission of alpha, beta or gamma radiation from an unstable nucleus

random process: a process that happens at a random rate and in random directions; the timing and direction of the next emission cannot be predicted

beta particle (β-particle): a high speed electron that is emitted by an atomic nucleus during radioactive decay

gamma ray (γ-ray): electromagnetic radiation emitted by an atomic nucleus during radioactive decay

An atom of a radioactive substance emits either an α-particle or a β-particle. In addition, it may emit some energy in the form of a γ-ray. The γ-ray is usually emitted at the same time as the α-particle or β-particle, but it may be emitted some time later.

When an atom of a radioactive substance decays by α- or β-decay, it becomes an atom of another element. This is because the number of protons in the nucleus changes.

α-particles have a much greater mass than beta particles, so they travel more slowly. γ-rays, like all electromagnetic waves, travel at the speed of light

Questions

4 Copy and complete the following sentences.

Radioactive decay happens when a nucleus is ______. This may be because it is too massive or because it contains too many ______

An α-particle consists of ______ and ______. A β-particle is an ______. γ-radiation is a form of high frequency ______ radiation

5 A β-particle is identical to an electron. How is it different to most electrons?

6 Which type of radiation travels at the speed of light?

Penetrating power

When physicists were trying to understand the nature of radioactivity, they noticed that radiation can pass through solid materials. Different types of radiation can penetrate different thicknesses of materials.

- α-particles are absorbed most easily. They can travel about 5 cm in air before they are absorbed. They are absorbed by a thin sheet of paper. α-particles cannot penetrate skin.
- β-particles can travel fairly easily through air or paper. But they are absorbed by a few millimetres of metal such as aluminium.
- γ-radiation is the most penetrating. It takes several centimetres of a dense metal like lead, or several metres of concrete, to absorb most of the gamma radiation.

Figure 23.6 shows the penetrating power of each type of radiation.

Figure 23.6: The penetrating power of γ-radiation is the greatest. α radiation has the least amount of penetrating power. This is related to their ability to ionise the materials they are passing through

Ionisation

When radiation passes through air, it may knock electrons out of atoms. This means ions are formed. This process is called ionisation.

- α-particles are the most ionising.
- γ-radiation is the least ionising.

As the radiation emitted by the nuclei of radioactive substances causes the ionisation of the materials that absorb it, it is often known as **ionising nuclear radiation**. X-rays also cause ionisation in the materials they pass through, and so they are also classed as ionising radiation. X-rays are very similar to γ-rays. However, X-rays usually have less energy (longer wavelength) than γ-rays, and they are produced by X-ray machines, stars and so on, rather than by radioactive substances.

When something has been exposed to radiation, it has been irradiated. Although it absorbs the radiation, it does not itself become radioactive. Things only become radioactive if they absorb a radioactive substance. So you do not become radioactive if you absorb cosmic rays (which you

do all the time). But you do become radioactive if you consume a radioactive substance. Coffee, for example, contains tiny but measurable amounts of radioactive potassium. You become contaminated by the coffee.

How ionisation happens

To explain the ionising effect of each type of radiation we need to consider their kinetic energy and their charge.

Name	Mass	Speed / m/s	Charge
α	approx. (mass of proton) × 4	$\sim 3 \times 10^7$	+2
β	approx. (mass of proton) ÷ 1840	$\sim 2.9 \times 10^8$	−1
γ	0	3×10^8	0

Table 23.2: Properties of ionising radiation.

Consider an α-particle passing through the air. An α-particle is the slowest moving of all the three radiations and has the largest charge. As the α-particle collides with an air molecule, it may knock an electron from the air molecule, so that it becomes charged. The α-particle loses a little of its energy. It must ionise thousands of molecules before it loses all of its energy and comes to a halt. α-radiation is the most strongly ionising radiation.

A β-particle can also ionise air molecules. However, it is less ionising for two reasons: its charge is much less than that of an α-particle, and it moves faster. This means that it is more likely to travel straight past an air molecule without interacting with it. This is why β radiation can travel further through air without being absorbed.

γ-radiation is uncharged and it moves fastest of all. This means that it is the least readily absorbed in air, and therefore is the least ionising. Lead is a good absorber because it is dense (its atoms are packed closely together), and its nuclei are relatively large, so they present an easy target for the γ-rays.

You should be able to see the pattern linking ionising power and absorption:

- α-radiation is the most strongly ionising, so it is the most easily absorbed and the least penetrating.
- γ-radiation is the least strongly ionising, so it is the least easily absorbed and the most penetrating.

Using, moving and storing radioactive materials safely

Any element comes in several forms or isotopes (see Section 22.2). Some may be stable, but others are unstable, that is, they are radioactive. For example, carbon has two stable isotopes (carbon-12 and carbon-13), but carbon-14 is an unstable isotope. Unstable (radioactive) isotopes are known as **radioisotopes**.

ionising nuclear radiation: radiation, emitted by the nucleus which can cause ionisation; alpha or beta particles, or gamma rays

radioisotope: a radioactive isotope of an element

Effects of radioisotopes on cells

To use radioisotopes safely, we need to understand how they affect cells. There are three ways in which radiation can damage living cells.

- An intense dose of radiation causes a lot of ionisation in a cell, which can kill the cell. This is what happens when someone suffers radiation burns. The cells affected simply die, as if they had been burned. If the sufferer is lucky and receives suitable treatment, the tissue may regrow.
- If the DNA in the cell nucleus is damaged, the mechanisms that control the cell may break down. The cell may divide uncontrollably and a tumour forms. This is how radiation can cause cancer.
- If the affected cell is a gamete (a sperm or egg cell), the damaged DNA of its genes may be passed on to future generations. This is how radiation can produce genetic mutations. Occasionally, a mutation can be beneficial to the offspring, but more often it is harmful. A fertilised egg cell may not develop at all, or the baby may have some form of genetic disorder.

We are least likely to be harmed by α radiation coming from a source outside our bodies. This is because the radiation is entirely absorbed by the layer of dead skin cells on the outside of our bodies (and by our clothes). However, if an α source gets inside us, it can be very damaging, because its radiation is highly ionising. That is why radon and thoron gases are so dangerous. We breathe them into our lungs, where they irradiate us from the inside. The result may be lung cancer.

Today, we know much more about radiation and the safe handling of radioactive substances. Knowing how to reduce the hazards of radiation means that we can learn to live safely with it and put it to many worthwhile purposes.

Knowing about the radiation produced by radioactive materials helps us know how to handle them as safely as possible. Anyone working with, or being exposed to, ionising radiation must take safety precautions, such as shielding, or limiting their exposure time. Figure 23.7 shows some of these precautions.

Figure 23.7a: Radiation suits are worn in contaminated areas. **b:** Radiographers operate equipment from a separate room **c:** School laboratory sources are stored in lead-lined wooden boxes and locked away in a labelled metal cabinet when not in use The tweezers allow the teacher to handle the sources at a safe distance **d:** Radioactive material must be clearly marked when it is being transported

Safety precautions

Table 23.3 shows common safety precautions when dealing with radioactive material

Safety precaution	Explanation
workers in contaminated areas wear protective suits	The suit will absorb radiation. Different materials can be used depending on the type of radiation. For γ-rays, lead-lined suits can be used.
radioactive hazard labels	These warn people of the danger so they can stay at a safe distance and reduce the time they are near the source for.
photographic film dosimeter badges	These monitor the amount of exposure a person has had. Once the safe limit is reached, workers may be transferred to other areas.
record keeping	Schools are required to record how long radioactive sources were used for, and by whom. This allows them to ensure no-one is exposed for too long.
remote operating of scanners	The operator usually controls the scanner from a separate area This increases their distance from the source. They may also be behind a screen which will absorb some of the radiation.
storage boxes for sources	Radioactive sources must be stored securely, usually surrounded by lead to absorb most of the radiation.

Table 23.3: Safety precautions for dealing with radioactive material.

Radioactive decay equations

Radioactive decay can be described using balanced equations with the nuclear notation we used in Chapter 22. To write these equations we need to consider the effect of each emission on the nucleus emitting it

- α-decay. two protons and two neutrons are emitted. The proton number decreases by 2 and the nucleon number decreases by 4.
- β-decay. a neutron splits into a proton and an electron. the electron is emitted The proton number increases by 1 and the nucleon number remains the same
- γ-decay this is the emission of energy from the nucleus and it does not change the particles in the nucleus

These changes all lead to the nucleus becoming more stable

Here is an example of an equation for **alpha decay**:

$^{241}_{94}Am \rightarrow {}^{237}_{92}U + {}^{4}_{2}He$ + energy

This represents the decay of americium-241, the isotope used in smoke detectors. It emits an α-particle (represented as a helium nucleus) and becomes an isotope of uranium. An α-particle can be represented as $^{4}_{2}He$ or $^{4}_{2}\alpha$.

Notice that the numbers in this equation must balance because we cannot lose mass or charge. So:

nucleon numbers: $241 \longrightarrow 237 + 4$

proton numbers $94 \longrightarrow 92 + 2$

Here is an example of an equation for **beta decay**

$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$ + energy

This is the decay that is used in radiocarbon dating. A carbon-14 nucleus decays to become a nitrogen-14 nucleus. The β-particle, an electron, is represented by $^{0}_{-1}e$ or $^{0}_{-1}\beta$. If we could see inside the nucleus, we would see that a single neutron has split into a proton and an electron. So

$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$

For each of these two β-decay equations, you should be able to see that the nucleon numbers and proton numbers are balanced We say that, in radioactive decay, nucleon number and proton number are conserved

alpha decay: the decay of a radioactive nucleus by the emission of an α-particle

beta decay: the decay of a radioactive nucleus by the emission of a β-particle

A radioisotope of thorium ($^{229}_{90}Th$) decays by emitting an α-particle. The resulting nucleus is also unstable and emits a beta particle. Write equations for the two emissions.

Step 1: In α-emission ($^{4}_{2}\alpha$) the proton number decreases by 2 (in this case, from 88 to 89) From the Periodic Table. we can see that Radium (Ra) has the proton number 88

The nucleon number decreases by 4 (in this case, from 229 to 225)

Step 2: In β-emission ($^{0}_{-1}\beta$) the proton number increases by 1 (in this case from 88 to 89) From the Periodic Table, we can see that Actinium (Ac) has the proton number 89

The nucleon number remains the same

Answer

α-emission: $^{229}_{90}Th \rightarrow {}^{225}_{88}Ra + {}^{4}_{2}\alpha$

β-emission: $^{225}_{88}Ra \rightarrow {}^{225}_{89}Ac + {}^{0}_{-1}\beta$

Deflecting radiation

How can we tell the difference between these three types of radiation? One method is to see how they behave in electric and magnetic fields

Because they have opposite charges, α and β-particles are deflected in opposite directions when they pass through an electric field (Figure 23.8a) Positively charged α-particles are attracted towards a negatively charged plate, while negatively charged β-particles are attracted towards a positively charged plate. β-particles are deflected more than α-particles as the are lighter. γ-rays are not deflected because they are uncharged.

α- and β-particles are charged, so, when they move, they constitute an electric current Because of their opposite signs, the forces on them in a magnetic field are in opposite directions (Figure 23.8b). This is an example of the motor effect (Chapter 20). The direction in which the

particles are deflected can be predicted using Fleming's left-hand rule. As in an electric field, γ-rays are not deflected because they are uncharged

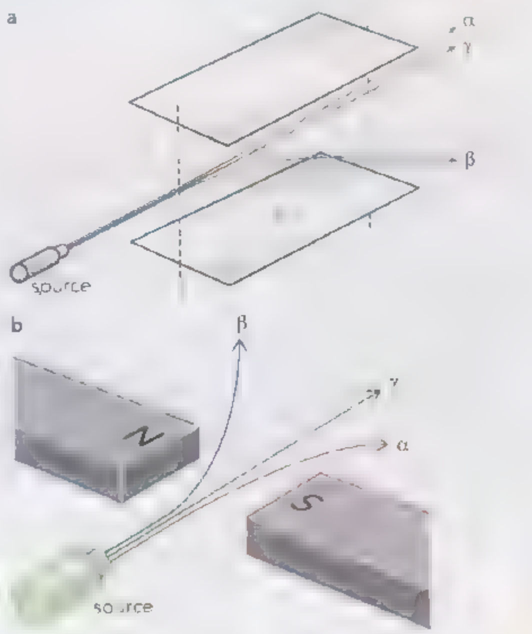


Figure 23.8: α- and β-radiations are deflected in opposite directions. **a:** In an electric field. **b:** In a magnetic field.

Questions

7 Explain why emission of α- or β-particles changes the nucleus to one of a different element

8 The equation represents the decay of a polonium nucleus to form a lead nucleus. An α-particle is emitted

$$^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb} + {}^{\square}_{\square}\boxed{} + \text{energy}$$

- **a** Copy and complete the equation.
- **b** Show that the proton numbers are equal on each side of the equation
- **c** Show that the nucleon numbers are equal on each side of the equation

9 Write a balanced nuclear equation to show what happens to the polonium isotope $^{218}_{84}\text{Po}$ when it emits a β-particle

10 γ-rays and X-rays are both forms of ionising radiation.

- **a** State one way in which they are similar
- **b** State one way in which they are different

11 Two beams of ionising radiation are passed between charged metal plates. They are deflected, as shown in Figure 23.9

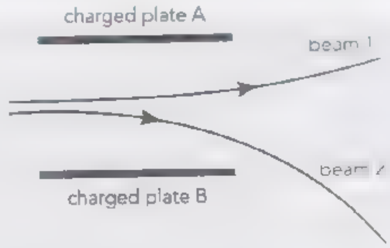


Figure 23.9

- **a** Name the type of radiation for each beam
- **b** State the polarity of each of the plates.
- **c** Name the type of radiation which would not be deflected by the plates.

12 Figure 23.10 shows a radiation detection badge

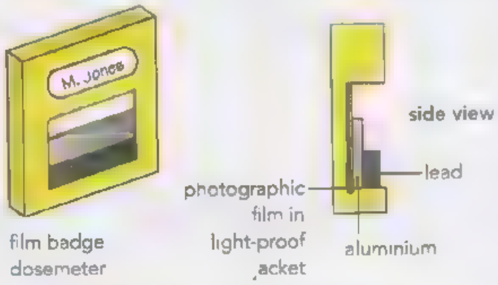


Figure 23.10: A radiation detection badge

- **a** Explain what you would see if the film inside the badge was developed if the wearer had been exposed to:
  - i β-radiation
  - ii γ-radiation.
- **b** Suggest a reason why the badge is not suitable for detecting exposure to alpha radiation.

23.3 Activity and half-life

The **activity** of a radioactive source is the rate at which its nuclei decay. This can be monitored using a Geiger counter which measures the count rate, the number of emissions detected each second (or minute).

The Geiger counter will not detect every emission, so activity and count rate are not equal, but count rate is used to monitor activity

The activity of a source decreases with time. As nuclei decay and become stable, there are fewer unstable nuclei, so there are fewer decays each second. The count rate and activity both decrease following the same pattern as the number of undecayed atoms.

All radioactive substances decay with the same pattern, as shown in Figure 23.11a The graph shows that the amount of a radioactive substance decreases rapidly at first, and then more and more slowly. In fact, because the graph tails off more and more slowly, we cannot say when the last atoms will decay. Different radioactive substances decay at different rates, some much faster than others, as shown in Figure 23.11b.

We cannot say when the substance will have entirely decayed. We have to think of another way of describing the rate of decay. As shown on the graph in Figure 23.11a, we identify the **half-life** of the substance.

The half life of a radioactive isotope is the average time taken for half of the atoms in a sample to decay, or the time for its activity or count rate to halve.

Half-lives can vary from a fraction of a second to thousands of years. Uranium decays slowly because it has a very long half-life. The radioactive samples used in schools usually have half-lives of a few years, so that they have to be replaced when their activity has dropped significantly. Some radioactive substances have half-lives that are less than a microsecond. No sooner are they formed than they decay into something else.

activity: the rate at which nuclei decay in a sample of a radioactive substance

half-life: the average time taken for half the atoms in a sample of a radioactive material to decay

Explaining half-life

After one half-life, half of the atoms in a radioactive sample have decayed. However, this does not mean that all of the atoms will have decayed after two half-lives. From the graph of Figure 23.11a, you can see that one-quarter will still remain after two half-lives. Why is this?

Figure 23.12 shows one way of thinking about what is going on. Imagine that we start with a sample of 100 undecayed atoms of a radioactive substance (white circles in Figure 23.12a). They decay randomly (black circles in Figure 23.12b–d) - each undecayed atom has a 50% chance of decaying in the course of one half-life. So, looking at the panels in Figure 23.12, we can describe the decay like this:

- At the start, in Figure 23.12a, there are 100 undecayed atoms.
- After one half-life, in Figure 23.12b, a random selection of 50 atoms has decayed.
- During the next half-life, in Figure 23.12c, a random selection of half of the remaining 50 atoms decays, leaving 25 undecayed.
- During the third half-life, in Figure 23.12d, half of the remaining atoms decay, leaving 12 or 13. (Of course, you cannot have half an atom.)

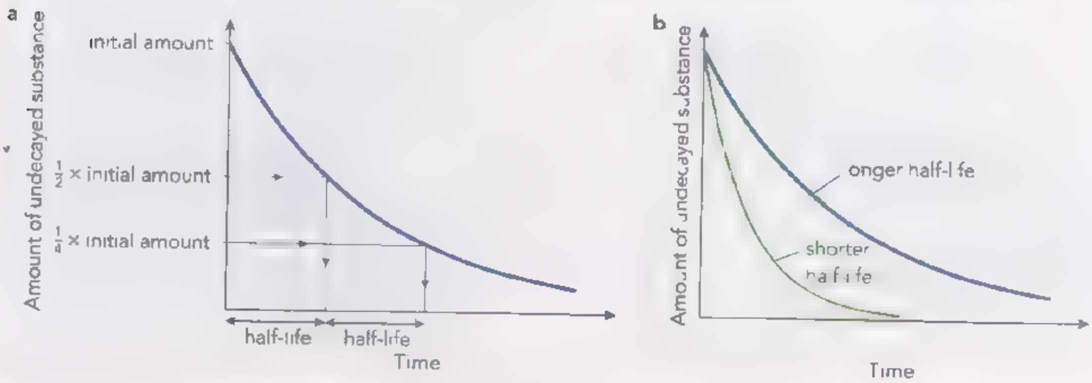


Figure 23.11a: A decay graph for a radioactive substance. A curve of this shape is known as an exponential decay graph. **b:** A steeper graph shows that a substance has a shorter half-life.

So the number of undecayed atoms goes 100, 50, 25, 12, ... and so on. It is because radioactive atoms decay in a random fashion that we get this pattern of decay. Notice that, just because one atom has not decayed in the first half-life does not mean that it is more likely to decay in the next half-life. It has no way of remembering its past.

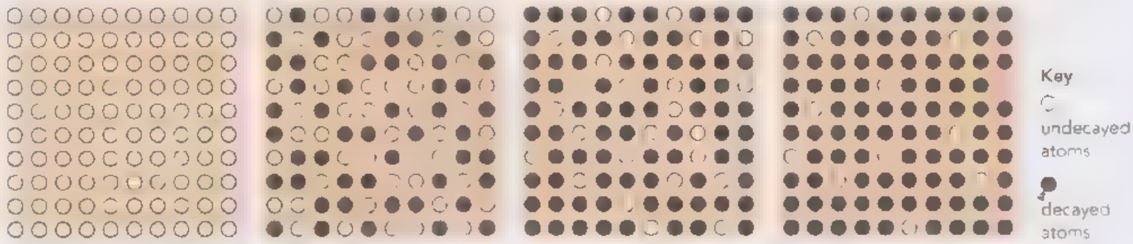


Figure 23.12: The pattern of radioactive decay comes about because the decay of individual atoms is random. Half of the atoms decay during each half-life, but we have no way of predicting which individual atoms will decay.

The count rate from a radioactive source is recorded for ten days. Figure 23.13a shows the results.

Use the graph to find the half-life of the source.

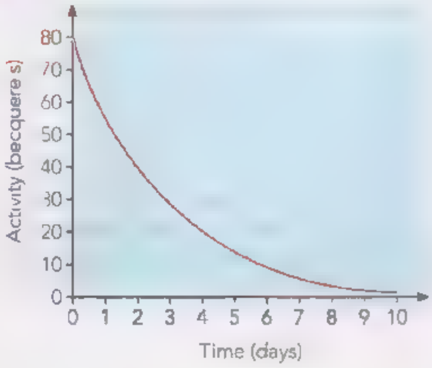


Figure 23.13a

Step 1: Calculate the count rate after one half-life.

The initial count rate is 80 count/s, so after one half-life it will have dropped to 40 count/s.

Step 2: Use the graph to find the time taken for the count rate to drop to 40 count/s.

The half-life is two days.

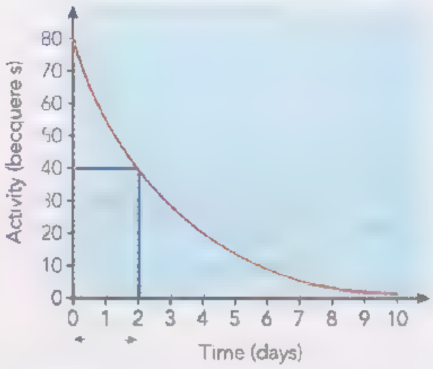


Figure 23.13b

CONTINUED

Step 3: Check this by finding the time taken for the count rate to halve again, from 40 count/s to 20 counts/s.

The count rate drops from 40 count/s to 20 count/s in two days, confirming that the half-life is two days.

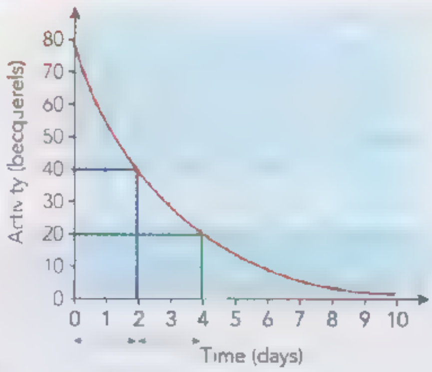


Figure 23.13c

Answer

The half-life is two days.

WORKED EXAMPLE 23.[illegible]

Strontium-90 has a half-life of 28 years. The count rate of a sample is 480 count/s. How long will it take for the count rate to drop to 30 count/s?

Step 1: Draw a table like Table 23.4 to work out the number of half-lives for the count rate to drop to 30 cps.

Number of half-lives	Count rate / count/s)
0	480
1	240
2	120
3	60
4	30

Table 23.4

So, the count rate has fallen to 30 count/s after four half-lives.

Step 2: Calculate how long this is in years.

One half-life is 28 years, so four half-lives: $4 \times 28 = 112$ years.

Answer

112 years

ACTIVITY 23.1

Modelling half-life

Radioactive decay is a random process. In this activity you will model radioactive decay using another random process – throwing dice or small cubes.

You will need a large number of dice – at least 100 – or small cubes with one side marked (as in Figure 23.14).

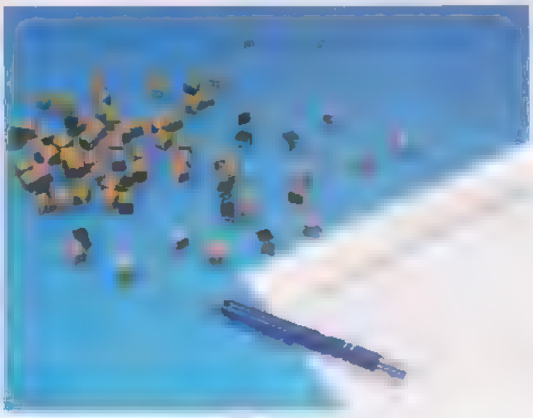


Figure 23.14: Using small cubes to model radioactive decay.

Place all the dice in a container, shake the container and throw the dice.

Any spinner showing 6, or cube with the marked side facing upwards, have 'decayed'. Count how many have decayed.

Create a table like Table 23.5 and record your results.

Throw number (time)	Number decaying (activity)	Number remaining (N)

Table 23.5

Repeat until all the dice have decayed.

Draw two graphs:

- activity against time
- number of 'nuclei' remaining against time.

Questions

1. What do you notice about the two graphs?
2. Calculate the half-life from each graph. What do you notice?

Corrected count rate

The count rate recorded by a Geiger counter will include background radioactivity as well as the count rate from the radioactive source. Often the background count is negligible in comparison to the activity of the source. If the background count is being taken into account, it should be subtracted from the Geiger counter measurements.

corrected count rate = measured count rate − background count rate

WORKED EXAMPLE 23.4

A scientist monitored a radioactive source every ten minutes using a Geiger counter. She recorded the following readings.

Time / min	0	10	20	30	40	50	60
Count rate / count/min	330	230	165	120	92	70	56

After the experiment she recorded a background count of 30 count/min.

Plot a graph of corrected count rate against time and use it to find the half-life of the source.

16 Carbon has two isotopes, carbon-12 and carbon-14. Carbon-14 is radioactive. The proportion of the two isotopes in living things remains constant while they are alive, but when they die, the proportion of carbon-14 drops as the isotope decays. Archaeologists studying a bone find it emits 20 count/s, whereas a similar modern bone emits 80 count/s.

The half-life of carbon-14 is 5700 years. Use this to estimate the age of the bone that the archaeologists found.

23.4 Using radioisotopes

Radioisotopes at work

Now we will look at some of the many uses of radioisotopes. We will look at these uses in four separate groups, related to:

- their different penetrating powers
- the damage their radiation causes to living cells
- the fact that we can detect tiny quantities of radioactive substances
- radioactive decay and half-life

Uses related to penetrating power

Smoke detectors

These are often found in domestic kitchens, and in public buildings such as offices and hotels. If you open a smoke detector to replace the battery, you may see a yellow and black radiation hazard warning sign (Figure 23.16a). The radioactive material used is americium-241, a source of α-radiation. Figure 23.16b shows how the smoke detector works.

The Americium source used in smoke detectors has a long half-life - about 430 years. This means that the count rate from the source will not drop significantly over the time the detector is in use.

Figure 23.16a: The inside of a smoke detector. The source of radiation is a small amount of americium-241.
b: Block diagram of a smoke detector. The alarm sounds when smoke absorbs the α radiation.

- Radiation from the source falls on a detector. Since α-radiation is charged, a small current flows in the detector. The output from the processing circuit is off, so the alarm is silent.
- When smoke enters the gap between the source and the detector, it absorbs the α-radiation. Now no current flows in the detector, and the processing circuit switches on, sounding the alarm.

In this application, a source of α-radiation is chosen because α-radiation is easily absorbed by the smoke particles.

Thickness measurements

In industry, β-radiation is often used in to measure thickness. Manufacturers of paper need to be sure that their product is of a uniform thickness. To do this β-radiation is directed through the paper as it comes off the production line. A detector measures the amount of radiation getting through.

If the paper is too thick, the radiation level will be low and an automatic control system adjusts the thickness. The same technique is used in the manufacture of plastic sheeting and aluminium foil. β-radiation is used in this application because α-radiation would be absorbed entirely by the paper, plastic or aluminium.

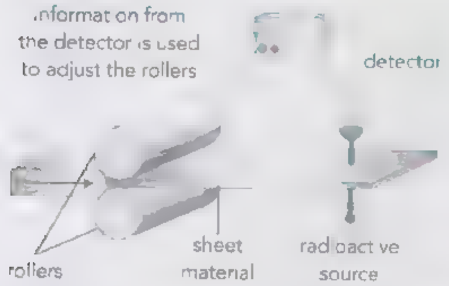


Figure 23.17: If the material gets too thick, less radiation will be detected. This will cause the rollers to be moved closer together, making the sheet thinner.

γ-radiation would hardly be affected, because it is the most penetrating.

Sheet steel factories use a similar system but with a γ source.

Fault detection

Sometimes γ-rays are used to detect faults in manufactured goods. Figure 23.18 shows an example, where engineers are looking for any faults in some pipework. If there is a fault, radiation will escape through the fault. A photographic film is strapped to the outside of the pipe and the radioactive source is placed on the inside. When the film is developed, it looks like an X-ray picture, and shows any faults in the welding.

Figure 23.18: Checking for faults in a metal pipe. The γ-ray source is stored in the black box in the foreground, but can be pushed through the pipe to reach the part that needs checking.

Uses related to cell damage – radiation therapy

Cancer treatment

The patient shown in Figure 23.19 is receiving radiation as part of a treatment for cancer. A source of γ-rays (or X-rays) is directed at the tumour that needs to be destroyed. The source moves around the patient, always aiming at the tumour. In this way, other tissues receive only a small dose of radiation. Radiation therapy is often combined with chemotherapy (using drugs to target and kill the cancerous cells).

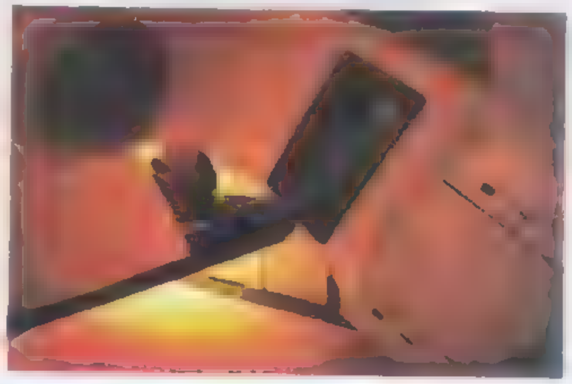


Figure 23.19: Radiation can cause cancer, but it can also be used in its cure. This patient is being exposed to γ-rays from a radioactive source.

Food irradiation

This is a way of preserving food. Food often decays because of the action of microbes. These can be killed using intense γ-rays. Because these organisms are single-celled, any cell damage kills the entire organism. Different countries permit different foods to be irradiated. The result is sterile food, which has been used on space missions (where long-life is important) and for some hospital patients whose resistance to infection by microbes may be low. Figure 23.20 shows a display from the Nehru Science Centre in Mumbai which demonstrates the advantages of irradiating food.

Figure 23.20: The microbes which would cause decay have been killed by radiation in the top sample

Sterilisation

Sterilisation of medical products works in the same way as food irradiation. Syringes, scalpels and other instruments are sealed in plastic bags and then exposed to gamma radiation. Any microbes present are killed, so that, when the packaging is opened, the item is guaranteed to be sterile. γ-radiation is used as it can penetrate the plastic and can pass through the equipment, making sure all parts are sterilised.

Figure 23.21: The sealed package ensures the syringe remains sterile once γ-rays have killed all pathogens.

Uses related to detectability – radioactive tracing

Every time you hear a Geiger counter click, it has detected the radioactive decay of a single atom. This means that we can use radiation to detect tiny quantities of substances, far smaller than can be detected by chemical means. Such techniques are often known as radioactive tracing. This has uses in medicine and engineering.

Medicine

The diagnosis of some diseases may be carried out using a source of γ-radiation. The patient is injected with a radioactive chemical and a scanner is used to trace the path of the chemical. Figure 23.22 shows a scan of a patient with a kidney blockage. The tracer technetium-99 is injected into the patient's blood. The scan shows that the tracer is not passing through the kidney shown on the right as well as it is through the other kidney. This indicates that there is a blockage. The technetium isotope used has a relatively short half-life – about six hours. This is long enough for it to be used to trace the blockage, but it does not remain radioactive very long inside the patient's body.

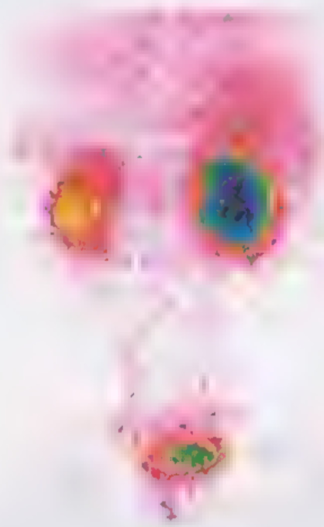


Figure 23.22: The tracer can be detected in both kidneys and the bladder. More γ – rays are detected from the kidney seen on the right, suggesting a problem there.

Engineering

Engineers may want to trace underground water flow, for example. They may be constructing a new waste dump, and they need to be sure that poisonous water from the dump will not flow into the local water supply. Under high pressure, they inject water containing a radioactive chemical into a hole in the ground (Figure 23.23). Then they monitor how it moves through underground cracks using γ-detectors at ground level.

Figure 23.23: Detecting the movement of underground water. Engineers are investigating how water moves underground. This can also affect the stability of buildings on the site. Water containing a source of γ-radiation is pumped underground and its passage through cracks is monitored at ground level.

Uses related to radioactive decay – half-life and radiocarbon dating

Because radioactive substances decay at a rate that we can determine, we can use them to discover how old objects and materials are. The best-known example of this is **radiocarbon dating**.

All living things contain carbon. Plants get this from atmospheric carbon dioxide, which they use in photosynthesis. Plant-eating animals get it from the plants they eat to build their bodies. Meat-eating animals get it from their prey. Most carbon is carbon-12, which is not radioactive. A tiny amount is radioactive (carbon-14), which has a half-life of 5700 years. It emits β-radiation.

When a living organism dies, the carbon-14 in its body decays. As time passes, the amount remaining decreases. We can measure the amount remaining, and then work out when the organism was alive.

There are two ways to measure the amount of carbon-14 present in an object:

- by measuring the activity of the sample using a detector such as a Geiger counter
- by counting the number of carbon-14 atoms using a mass spectrometer (a large machine that uses magnetic fields to separate atoms according to their mass and charge).

The Turin Shroud was famously dated in 1988 using a mass spectrometer. The shroud was dated to 1325 ± 33 CE, which matches the dates of the earliest historical records of its existence.

Problems can arise with radiocarbon dating. It may be that the amount of carbon-14 present in the atmosphere was different in the past. Nuclear weapons testing added extra carbon-14 to the atmosphere during the 1950s and 1960s. This means that living objects that died then have an excess of carbon-14, making them appear younger than they really are.

radioactive tracing: using a radioisotope to investigate a problem

radiocarbon dating: a technique that uses the known rate of decay of radioactive carbon-14 to find the approximate age of an object made from dead organic material

Other radioactive dating techniques

Geologists use a radioactive dating technique to find the age of some rocks. Many rocks contain a radioactive isotope, potassium-40, which decays by β emission to a stable isotope of argon. Argon is a gas, and it is trapped in the rock as the potassium decays.

The rocks of interest form from molten material, for example, in a volcano. There is no argon in the molten rock because it can bubble out. After the rock solidifies, the amount of trapped argon gradually increases as the potassium decays. Geologists take a sample and measure the relative amounts of argon and potassium. The greater the proportion of argon, the older the rock must be.

Questions

17 A smoke detector uses an α-source. Explain why:

- **a** a β- or γ-source would not work
- **b** it is safe to have this type of smoke detector in your home
- **c** the source used must have a half-life of years rather than days.

18 Describe what would happen if the sheet shown in Figure 23.17 became too thin.

19 When medical equipment is to be sterilised, it is first sealed in a plastic wrapper. Why does this not absorb the radiation used?

Demystifying radioactivity

We have known about rad oactiv ty for just over a century. In that time it has attracted a lot of sensational attention as an amazing cure-all, an invisible kil er or for its fictional ability to mutate humans or animals into monsters.

Figure 23.24: This is the international warning sign for ionising rad ation

Over the last century we have learnt that, although dangerous, ionising radiation can be very useful, and if hand ed correctly, it can be safe.

Your task is to prepare a television segment or magazine artic e about radioactivity aimed at teenagers to explain the science of radioactivity and its uses and dangers.

You should:

- describe and il ustrate the three types of radioactive emission
- explain how we can use knowledge about their penetrating power to use and store sources safely
- explain what is meant by half-life and why some radioactive waste must be stored securely for many years
- include as many practical examples of the uses of radioisotopes as you can.

You shou d present your work as a video or a group presentation to the class, or in a written article.

Much of the fear wh ch surrounds radioactive materials s made worse by the language surrounding it. Words such as 'mutation' and 'half-life' are not in everyday use and can add to the fee ing that radiation is a weird scientific threat. To counter th s, your presentation should include and explain the following key terms.

- radioactive
- α-particle
- β-particle
- γ-ray
- ionisation
- mutation
- radioactive isotope
- nuclear decay
- half-life
- background radiation.

We are surrounded by ionising background radiation from natural and man-made sources.
Unstable isotopes decay randomly.
Radioactive decay leads to three types of emissions – α-particles, β-particles and γ-rays.
α and β emissions change the nucleus to that of a different element.
α and β emissions can be described using balanced nuclear equations.
The half-life of a radioactive source is the time taken for half its radioactive nuclei to decay
α, β and γ-radiation can all ionise cells, leading to mutations and tumours. Safety precautions must be taken when using radioactive materials.
When used safely, radioactive materials have many uses, particularly in medicine and engineering.

1 Which of the following is a natural source of background radiation? [1]

A medical X rays

B nuclear power stations

C cosmic rays

D nuclear weapons testing

2 Nuclear radiation can cause ionisation by knocking electrons out of atoms. Which type of radiation is least ionising? [1]

A α-particles

B β-particles

C γ-rays

D they all have the same ionising power

3 A source contains 240 g of a radioactive isotope. The half-life of the source is three hours. How much of the isotope will be left after 12 hours? [1]

A none   B 30 g   C 15 g   D 20 g

4 a Each of the statements below describe a type of radiation.

Type 1: Absorbed by a thin sheet of paper

Type 2: Absorbed by a thin sheet of metal

Which types of radiation are described in the statements?

	Type 1	Type 2
A	β-radiation	α-radiation
B	γ-radiation	β-radiation
C	α-radiation	β-radiation
D	β-radiation	γ-radiation

b Which statement is correct?

A γ-radiation is an electron emitted from the nucleus

B α-radiation has a negative charge

C γ-radiation has a positive charge

D β-radiation is an electron emitted from the nucleus [3]

[Total: 10]

*5 A radioisotope of radium has a half-life of 1600 years.

a **Define** what is meant by the term 'half life'. [1]

b The paint in a luminous watch face contains 20 mg of the radioisotope of radium. **Calculate** the mass that remains undecayed after 3200 years. [1]

c Radium emits ionising radiation. **State** how this can affect living cells. [1]

d **Describe** the safety precautions which must be taken when radioactive radium is used in a school laboratory. [2]

[Total: 5]

define: give precise meaning

calculate: work out from given facts, figures or information

state: express in clear terms

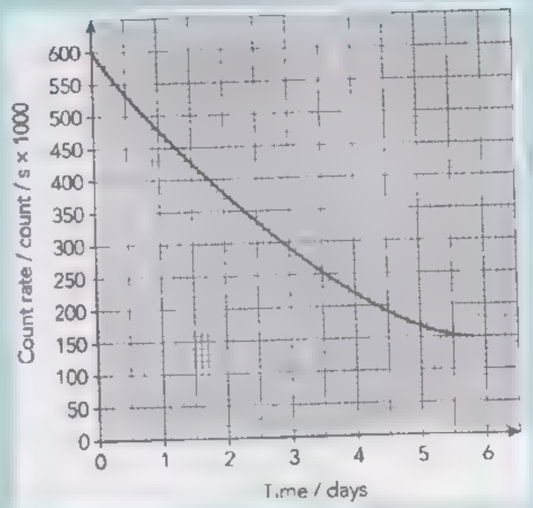
describe: state the points of a topic; give characteristics and main features

6 Gold has different isotopes. Gold-198 is radioactive and decays by β-emission.

a Name a particle which is identical to a β-particle [1]

b Name a material which could be used to stop β-particles, but which would not stop γ-rays. [1]

c The graph shows how the count rate from a sample of gold-198 changes with time



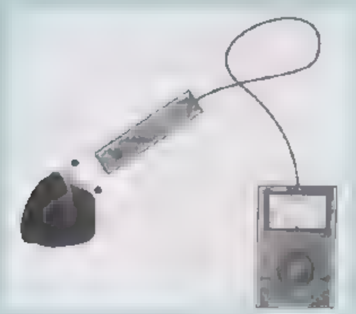
Use the graph to find the half-life of gold-198 [1]

[Total: 3]

7 α-particles are a type of ionizing nuclear radiation.

a Describe the structure of an α-particle [1]

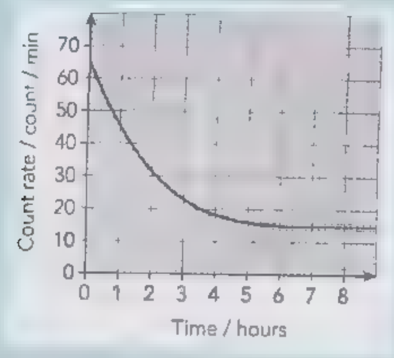
c Scientists test a rock with a Geiger counter and find that it is emitting radiation



They suspect it is α-radiation How could they test to confirm this? [2]

[Total: 6]

8 The graph shows the readings obtained when a radioactive isotope was monitored



a Name the measuring instrument used to obtain these results [1]

b A student wrongly calculates the half-life as 2 hours what the student has done wrong [2]

c From the graph, the correct half-life Draw a sketch graph to show your method [3]

[Total: 6]

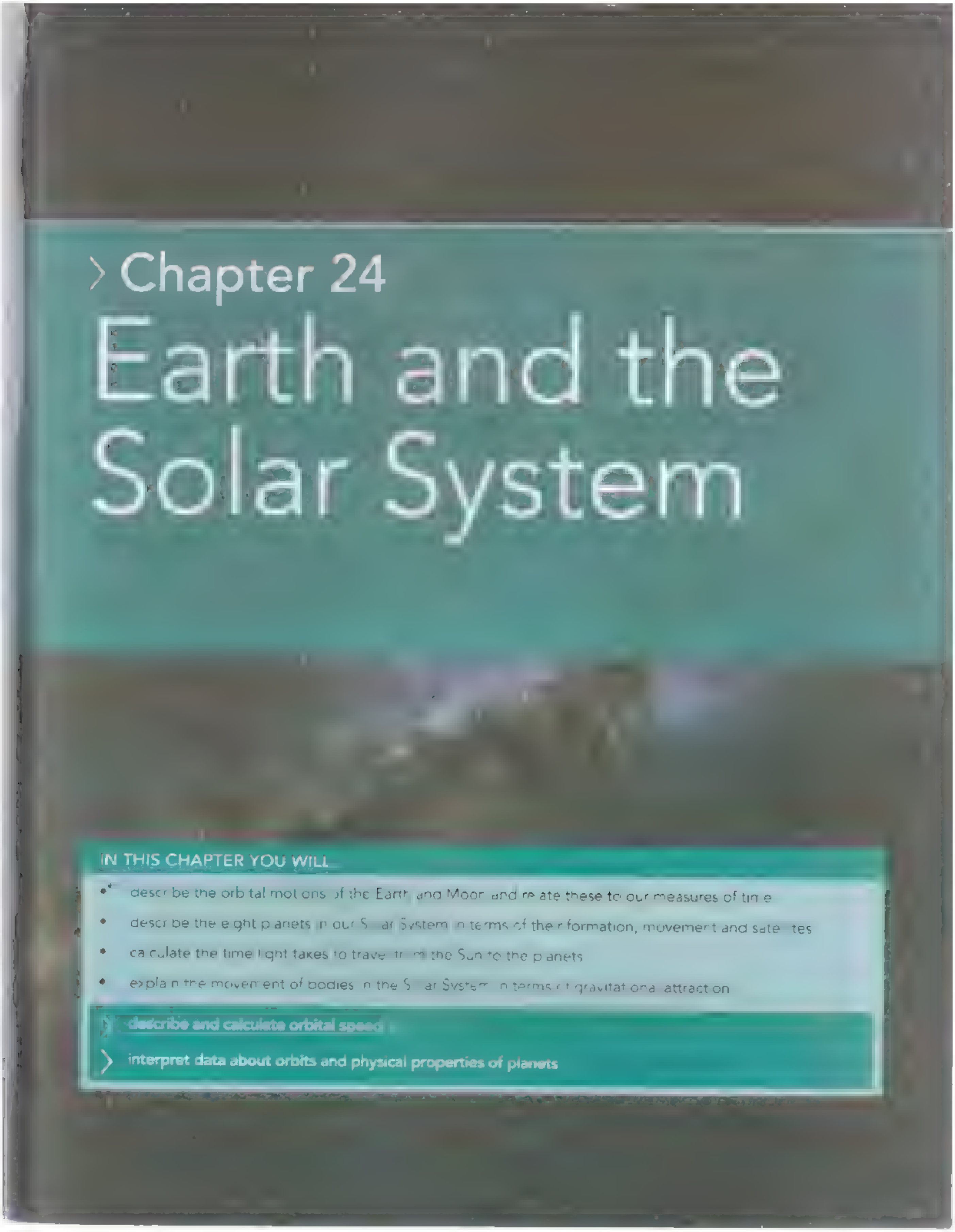
explain: set out purposes or reasons / make the relationships between things evident / provide why and / or how and support with relevant evidence

deduce: conclude from available information

[illegible]

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Recall the main sources of background radiation.	23.1			
State the units of count rate.	23.1			
Explain what it means to say radioactive emission is random.	23.2			
Describe the nature, ionising effect and penetration of α, β and γ.	23.2			
Describe how ionising radiation can be detected.	23.2			
Describe how α, β and γ are affected by electric and magnetic fields.	23.2			
State why some isotopes are radioactive and decay to become different elements.	23.2			
Describe how α- and β-emission change nuclei, using nuclear equations.	23.2			
Define the half-life of a radioactive source and use it in calculations.	23.3			
Describe the effects of ionising radiation on living cells, and the safety precautions which should be taken when using radioactive materials.	23.3			
Describe and explain practical uses of radioactive materials.	23.4			



> Chapter 24

Earth and the Solar System

IN THIS CHAPTER YOU WILL:

- describe the orbital motions of the Earth and Moon and relate these to our measures of time
- describe the eight planets in our Solar System in terms of their formation, movement and satellites
- calculate the time light takes to travel from the Sun to the planets
- explain the movement of bodies in the Solar System in terms of gravitational attraction

> describe and calculate orbital speed

> interpret data about orbits and physical properties of planets

Each of these pictures relates to our Solar System and our exploration of it. In groups, identify what each picture shows and write down a fact related to it.

Share your facts with the class. Award yourself a point for a correct fact and two points for a correct fact which no other groups have mentioned.

Figure 24.1: These pictures all relate to our Solar System and our exploration of it

HOW MANY PLANETS?

Figure 24.2: This artist's impression shows the Sun and the eight planets we now know orbit the Sun.

Humans have known about the first five planets, Mercury, Venus, Earth, Mars and Jupiter, for a long time as we can see them with the naked eye. In 1610, the newly invented telescope allowed Galileo Galilei to discover Saturn. Uranus was added by William Herschel in 1781. Careful observations of the orbit of Uranus showed it did not follow a smooth orbital path as the other planets did. Astronomers predicted this was due to the effect of the gravitational pull of another planet. They calculated where this should be and found Neptune in 1846. Tiny, distant Pluto was discovered in 1930 bringing the total to nine planets. And so it remained until 2006.

In the 1990s, several objects with similar mass to Pluto were discovered. This created a problem. Should these be named as planets, and if not, could Pluto still be classed as a planet? The International Astronomical Union decided a new definition for the title planet was needed. It came up with three rules. To be a planet, a body must:

- orbit the star (our Sun)
- have enough mass that its gravity pulls it into a spherical shape
- have a large enough gravitational pull to clear away any other objects of a similar size near its orbit around the Sun.

Pluto failed the third rule due to the discovery of an object named Eris, about the size of Pluto, orbiting close to Pluto. Pluto and Eris were both reclassified as a dwarf planets, leaving a total of eight planets.

Discussion questions

1 Why is it important to have international agreement about the definition of a planet? Are there any other areas where scientists have agreed standard definitions?

2 A lot of people felt that Pluto should have kept its status as a planet. What consequences would this have had?

24.1 Earth, Sun and Moon

Day and night

The most obvious sign of movement in the Solar System is the cyclical daily change from light to dark. It is not surprising that our ancestors thought the Sun travelled round the Earth. Each day we see the apparent movement of the Sun from rising in the east to setting in the west. We now know that this effect is caused by the Earth spinning on its **axis** (the imaginary line between the poles). The side of the Earth facing the Sun experiences daylight whilst the other side is in darkness. At sunrise at a particular spot on Earth, the Sun is just visible on the eastern horizon. As the Earth turns, the spot moves into the full glare of the Sun so the Sun appears directly overhead at midday. As the Earth continues to turn, the spot moves out of the direct sunlight until, at sunset, the Sun appears to slip below the western horizon.

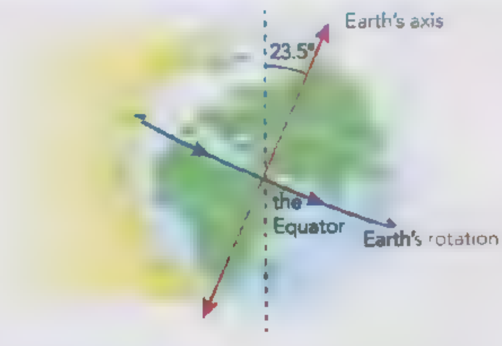


Figure 24.3: As light travels in straight lines, only half the Earth receives sunlight at any one time

As well as the daily changes, early civilisations were aware of periodic changes which happened over a longer time – the difference between seasons. The Earth orbits the Sun. It takes just over 365 days to complete one orbit. The seasons occur because of the tilt of the Earth's axis. Figure 24.4 shows how the seasons change as the Earth orbits the Sun

Consider a country in the northern hemisphere (the half of the Earth north of the Equator). In Figure 24.4a, due to the tilt of the Earth, it is tipped away from the Sun and the energy from the Sun's rays is more spread out, making it colder. This means that area receives fewer hours of sunlight. These countries are experiencing winter. In Figure 24.4c, the northern hemisphere is tipped towards the Sun, so it receives longer hours of more direct sunlight. These countries are experiencing summer

Years

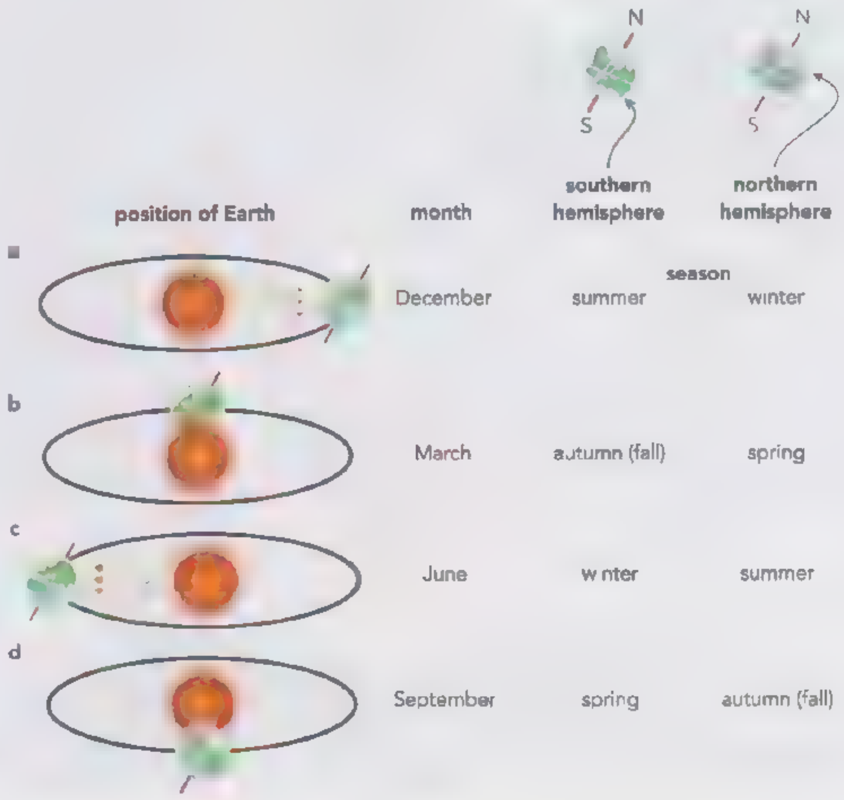


Figure 24.4: The Earth orbits the Sun every 365.25 days. The tilt of the Earth causes seasons.

axis: the imaginary line between the Earth's North and South poles

orbit: the path of an object as it moves around a larger object

hemisphere: half of a sphere; the Earth can be considered to be made of two hemispheres divided by the Equator

(the) Equator: an imaginary line drawn round the Earth halfway between the North Pole and the South Pole

Countries at the Equator do not experience seasons because the Sun's rays always hit them at the same angle. The seasonal differences are more apparent the further from the Equator you are. In the far north or south, seasons are so extreme that, in winter, the Sun is hardly seen and, in summer, it can be sunny at midnight. Figure 24.5 shows how, in Alaska, the Sun dips lower in the sky towards midnight but then starts to rise again.

Figure 24.5: This multiple exposure photograph shows the position of the Sun in the hours before and after midnight in Alaska in midsummer

Months

The most obvious object in our sky after the Sun is the Moon. The Moon features in many folk tales. It has often been seen as a mystical object due to its fainter light and its changing shape. With the benefit of telescopes and space travel, we know the Moon is a rocky sphere which we only see when it reflects light from the Sun. The Moon orbits Earth every 27.5 days. Its position relative to Earth changes the way it appears to us as different parts of it are illuminated by the Sun. This causes the changes called the phases of the Moon. The phases of the Moon are shown in Figure 24.6

Figure 24.6: The phases of the Moon. As the Moon orbits the Earth, the half of the Moon that faces the Sun will be lit up by the Sun. As the Moon moves, the shape of the light part, which can be seen from the Earth, changes. The outer circle of Moon diagrams shows how the Moon looks to an observer on Earth

phases of the Moon: the different ways the Moon looks when viewed from Earth over a period of one month

ACTIVITY 24.1

Modelling day, night and seasons

Use a lamp to represent the Sun and a ball with a rod through it to represent the Earth. Mark your position on the Earth using a pen or a piece of modelling clay. In a darkened area, hold the 'Earth' near to the 'Sun', and turn the Earth on its axis to model day and night.

Tilt the Earth on its axis and investigate the seasons by moving the Earth around the Sun. Investigate the difference in seasons between the southern and northern hemispheres

Figure 24.7: Model of the Earth and Sun

Questions

1 Copy and complete the following sentences.

A day is the time taken for the ____________

A month is the time taken for the ____________

A year is the time taken for the ____________

The Earth is tilted on its axis and this causes ____________ which do not occur at the Equator.

2 Explain why it is summer in the northern hemisphere when it is winter in the southern hemisphere. Include a drawing in your answer.

3 Look at the photograph of the Moon (Figure 24.8).

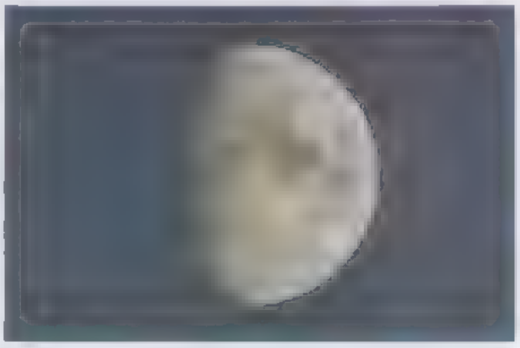


Figure 24.8: The Moon

a Which phase of the Moon is this?

b How many days are there from one full Moon to the next?

24.2 The Solar System

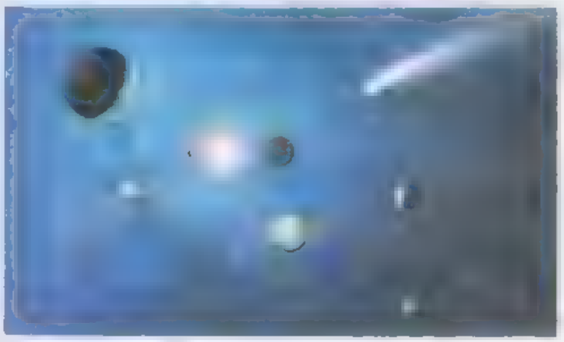


Figure 24.9: An artist's impression of the Solar System with a visiting comet. The picture is not to scale.

The Solar System consists of the Sun which is our star, and all the objects which orbit it. It includes the following.

- There are eight **planets**: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.
- There are **minor planets**, such as Pluto and Eris. In 2014, the International Astronomical Union recognised five dwarf planets but it is believed there are more than 200 in all.
- Moons that orbit planets and dwarf planets.
- Millions of **asteroids** and **meteoroids**: these are rocky objects which are smaller than planets. Most asteroids are found in the asteroid belt between the orbits of Mars and Jupiter.
- **Comets**, which are often described as giant snowballs, orbit the Sun in very irregular orbits. When they are furthest from the Sun, they are frozen balls of gas, rock and dust. As they get nearer to the Sun they heat up and leave a trail of dust and gases behind them. (Note: this trail of dust is **not** the tail of the comet: the tail always points away from the Sun, so could actually be at 90° to the motion of the comet.)

Figure 24.10a: Asteroids and meteoroids sometimes enter the Earth's atmosphere. Smaller meteoroids burn up in the Earth's atmosphere and are seen as shooting stars. **b:** It is believed that the dinosaurs became extinct due to a large asteroid hitting the Earth creating a huge crater and throwing up so much dust that the Sun's rays could not reach Earth for more than a year. **c:** Comet Hale Bopp was visible to the naked eye in the summer of 1995. It is not expected to be visible again soon as it takes 2533 years to orbit the Sun!

The Sun's gravitational pull

The orbits of the planets are almost circular. To move in a circle an object needs a force pulling it towards the centre of the circle. Imagine spinning a ball on the end of a piece of string. The ball will spin in a circle as long as you hold on. Once you let go, the ball will fly outwards. The force needed to keep the planets orbiting the Sun comes from the gravitational attraction of the Sun.

The formation of the planets

Evidence collected by astronomers suggests that the planets were formed at the same time as the Sun. The Solar System began as a nebula, which is a huge swirling ball of dust and gas. Most of this gas was hydrogen, but there were also other elements formed by fusion in other stars, which had exploded at the end of their life cycle, sending their contents out into the clouds of interstellar gas.

As gravity pulled this mass together, the centre formed a star. You will learn more detail about this in Chapter 25. The planets formed from the materials of the nebula which were not pulled into the Sun. The spinning motion of the dust and gas formed a flat, spinning ring disc known as an accretion disc. Gravity pulled dust and gas together so they joined to make rocks which then join to make larger rocks. The process of the dust and gas being pulled together by gravity is called accretion and it led to the formation of the inner, rocky planets. The intense heat forced some of the lighter materials further away and these formed the outer planets – the gas giants.

The four inner planets, Mercury, Venus, Earth and Mars, are small and rocky. After Mars there is the asteroid belt. This is made up of left over pieces of rock. The outer four planets, Jupiter, Saturn, Uranus and Neptune, are huge balls of gases. These planets are much bigger than the inner planets.

Figure 24.11: This artist's impression shows a star forming. The uneven, swirling mass of rock and gas around it is flattened by its rapid rotation into an accretion disc where the planets eventually form.

[illegible]

planet: a large spherical object that orbits the Sun without another similar object close to it

minor planet: an object which orbits the Sun but is not large enough or far enough from another object to be defined as a planet

asteroids and meteoroids: lumps of rock which orbit the Sun

comet: a ball of ice, dust and gas which orbits the Sun in a highly elliptical orbit

accretion disc: a rotating disc of matter formed by accretion

accretion: the coming together of matter under the influence of gravity to form larger bodies

Distances and times in the Solar System

Distances in the Solar System are almost unimaginably big. The Earth is approximately 150 million kilometres from the Sun. This is similar to circling the Earth 4000 times. Distances are often expressed in terms of how long it takes light to travel; one light-year is the distance travelled by light in a year. The next nearest star after the Sun is Proxima Centauri, which is 4.2 light-years from Earth. You will learn more about light-years in Chapter 25.

[illegible]

Calculate the time for light from the Sun to travel the 150 000 000 km to Earth. Give your answer in minutes.

Step 1: Write down what you know:

speed of light = 300 000 000 m/s

distance travelled = 150 000 000 km

Step 2: Convert distance to metres, so units are consistent.

150 000 000 km = 150 000 000 000 m

Step 3: Write the equation down and calculate the time taken:

$$\text{time taken} = \frac{\text{distance travelled}}{\text{speed}}$$

$$= \frac{150\,000\,000\,000\text{ m}}{300\,000\,000\text{ m/s}}$$

$$= 500\text{ seconds}$$

Step 4: Convert to minutes

$500 - 60 = 8.3$ minutes

Answer

8.3 minutes

Questions

4 The Moon is approximately 390 000 km from Earth. Calculate the time it takes for light to travel from the Moon to the Earth.

5 How long will it take for light from the Sun to reach:

a Mercury, which is approximately 60 000 000 km from the Sun

b Neptune, which is approximately 4 500 000 000 km from the Sun.

6 It takes sunlight 43 minutes to reach Jupiter. Calculate the distance from Jupiter to the Sun

7 Calculate how many kilometres a light-year is equivalent to.

More about the planets

Table 24.1 gives data about the planets in the Solar System. It shows how the planets differ from each other, for example looking up from the surface of Jupiter you might see 16 moons.

Forces

The Sun is at the centre of the Solar System. It is by far the most massive object in the Solar System and makes up about 99.8% of the mass of the Solar System. As gravitational attraction depends on mass, the gravitational field strength of the Sun is far larger than the field of any other object in the Solar System.

The planets, minor planets, asteroids and meteoroids and comets all orbit the Sun. They are held in orbit by the gravitational attraction of the Sun.

Like other non-contact forces such as magnetism and static electricity, gravitational attraction decreases with distance. This means that the outer planets experience less gravitational force from the Sun than the inner planets do.

Planet	Average orbital distance / million km	Orbital duration / years	Density / kg/m^3	Surface temperature / °C	Gravitational field strength at the surface of the planet / N/kg	Number of Moons
Mercury	58	0.2	5500	−18 to 460	4	0
Venus	108	0.6	5200	470	9	0
Earth	150	1	5500	−8 to 58	10	1
Mars	228	1.9	4000	−8 to −5	4	2
Jupiter	778	12	1300	15 to 20	26	16
Saturn	1427	30	700	−140	11	20
Uranus	2870	84	1300	−200	11	15
Neptune	4497	165	1700	−220	12	8

Table 24.1

Although the planets are small compared to the Sun, they are very massive objects. Jupiter has a mass of 1.9×10^{27} kg. The more massive the planet, the greater the gravitational force experienced by objects at its surface. On Earth we experience a force of 10 N/kg. On Earth a 60 kg student has a weight of 600 N. On Mercury, where gravity is 4 N/kg, the same student would weigh 240 N. The gravitational pull of planets is enough to cause moons to orbit them.

Orbits and energy

The orbits of the planets are not completely circular. Their shape is that of a slightly squashed circle, called an **ellipse**. The orbits are described as elliptical. The amount the orbit is squashed is called its **eccentricity**. Comets have very eccentric orbits. Comets travel far from the Sun and then return close to it.

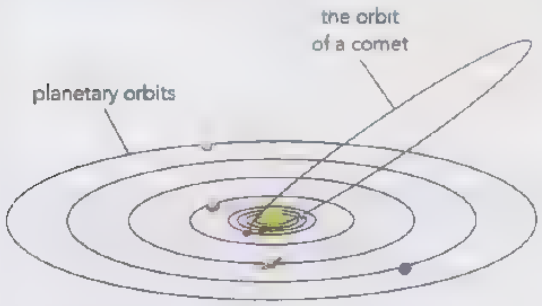


Figure 24.12: The orbit of Halley's comet is much more eccentric than those of the planets and minor planets

Why are orbits elliptical? To explain this, we need to think about the early swirling mass of the Solar System. Imagine an object moving past the Sun at high speed carried along by its own momentum from the explosive start of the universe. As it passes near the Sun the gravitational force of the Sun starts to act on the object and to pull it towards the Sun. This force also causes it to accelerate. This means the mass speeds up and its kinetic energy carries it slightly further out to the furthest point of the orbit. The object slows down and is pulled in again towards the Sun.

The Sun is not quite at the centre of a planet's elliptical orbit. There is a point close to the centre of an ellipse called the focus. The Sun is at the focus of the elliptical path of each of the planets. The planet moves closer to, and further away, from the Sun during each orbit.

The Sun's gravity pulls the object in, speeds it up and then the speed carries it on to the furthest part of the orbit.

The object's orbital speed is therefore greatest when it is nearest to the Sun and slowest when it is furthest from the Sun.

Comets, which have the most elliptical orbits of any body in the Solar System accelerate greatly as they approach the Sun and are slung back at high speed to the far reaches of their orbits.

A planet orbiting in space does not experience any friction or air resistance, so its energy remains the same throughout its orbit. It has two types of energy:

- kinetic energy
- gravitational potential energy.

When it is nearest the Sun, a planet has its minimum gravitational potential energy and is moving at its fastest so has its maximum kinetic energy. When it is at its furthest from the Sun, it has maximum gravitational potential and minimum kinetic energy.

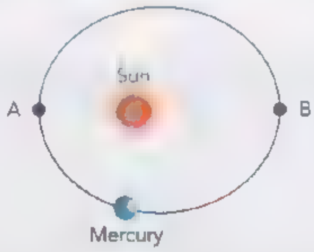


Figure 24.13: Mercury has the most elliptical orbit of any of the planets in the Solar System. At point A, it is 46 million km from the Sun, travelling at its fastest speed but with least potential energy. At point B, it is 70 million km from the Sun, travelling at its slowest speed but with most potential energy.

Speeds

The speed of a planet in orbit round a star is called its orbital speed (v). As the planets' orbits are almost circular, the distance they travel can be calculated if we know the average **orbital radius**, which is the average distance of the planet from the Sun, or the average radius of the orbit.

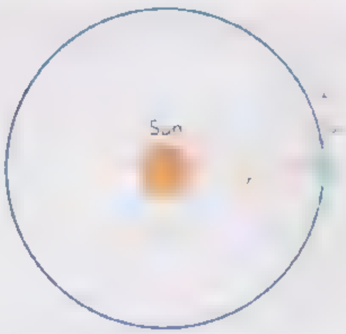


Figure 24.14: To calculate the orbital speed, we assume that the orbits are circular

The distance travelled by the planet is the circumference of its orbit. The circumference of a circle is equal to $2\pi r$.

If we also know the time for the planet to orbit the Sun – known as its **orbital period** (T) – we can calculate the speed:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

So, the average orbital speed v, can be calculated from its orbital period, T, and its average orbital radius r, using the equation:

$$v = \frac{2\pi r}{T}$$

KEY EQUATION

$$\text{average orbital speed} = \frac{2 \times \pi \times \text{orbital radius}}{\text{orbital period}}$$

$$v = \frac{2\pi r}{T}$$

KEY WORDS

ellipse: a squashed circle

eccentricity: a measure of how elliptical an orbit is

orbital radius: the average distance of the planet from the Sun

orbital period: the time taken for a planet to complete one full orbit of the Sun

[illegible]

Calculate the orbital speed of Earth.

Step 1: Write down what you know.

$r = 150\,000\,000$ km

$T = 1$ year

Step 2: Convert T to seconds.

1 year = $1 \times 365 = 365$ days

365 days = $365 \times 24 = 8760$ hours

8760 hours = $8760 \times 60 \times 60 = 31\,536\,000$ seconds

Step 3: Substitute values for T and r into the equation and calculate v.

$$v = \frac{2\pi r}{T}$$

$$= \frac{2\pi \times 150\,000\,000\text{ km}}{31\,536\,000\text{ s}}$$

$$= 30\text{ km/s}$$

Answer

30 km/s

Planetary patterns

Much of what astronomers have discovered has been through observing the skies, gathering huge amounts of data and then looking for patterns in the data. Ancient astronomers knew the planets were different from the stars because of the way their positions in the sky changed. Mercury was named by ancient Greeks after the messenger of the gods, which is a fitting name for the planet which orbits the Sun faster than any other. Sometimes we can learn as much from observations that are exceptions to a pattern as from those that fit our predictions.

The data in Table 24.1 can be used to investigate patterns in the properties and behaviours of planets. Plotting data on a **scatter graph** can give a clear indication of whether there is a correlation between two sets of data. For example, a graph of density against distance from the Sun (Figure 24.15) shows that there is not a clear correlation between the two. However, it is clear that the four inner rocky planets are more dense than the outer gas giants.

KEY WORDS

scatter graph: a way displaying two sets of data to see if there is a correlation, or connection

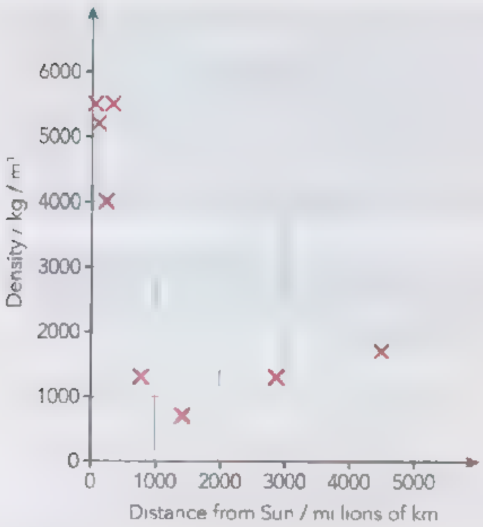


Figure 24.15: There is a pattern in this data but not a direct correlation.

Questions

8 a Name the force which causes planets to orbit the Sun.
  b What shape are planetary orbits?
  c How is the orbit of a comet different to the orbit of a planet?
  d Describe the energy changes in a comet as it orbits the Sun.

9 Calculate the weight of a 30 kg sheep on:
  a Earth
  b Mars
  c Jupiter.

10 Use information from Table 24.1 to calculate the orbital speeds in m/s of:
  a Venus
  b Saturn

11 Using Table 24.1, draw and comment on scatter graphs to investigate the relationship between:
  a orbital distance and average temperature
  b gravitational field strength and the number of moons.

PROJECT

Solar System quiz

Some great ways of learning are:

- finding information from a variety of sources
- summarising the information
- writing questions and answers on the information you have gathered
- answering questions written by your peers.

Figure 24.16

This task asks you to bring all these together to help you become an expert on our Solar System.

Make up a quiz about the Solar System. The quiz can be on paper, the computer, or on a mobile device such as phone or tablet (there are lots of good quiz making apps available). It should be aimed at students who have studied this chapter, and who have a good general knowledge. Spend some time revising and researching to find interesting facts to include. You may want to rate questions as 'easy', 'medium' or 'hard' and give more points for harder questions. You can include mathematical questions and questions which require data interpretation. You should include at least 20 questions. Think about how you will group your questions. You could include:

- A picture round: use pictures from the Internet or draw your own.
- Definitions: you could give a definition, such as, 'this is the time it takes for the Earth to orbit the Sun' or, 'this has the most elliptical orbit of any object in the Solar System', and ask what is being defined.

CONTINUED

- Facts about the planets: this could involve some questions for which the answers can be worked out from a data chart you supply.
- History of astronomical discoveries: use the Internet and this book to help you.

When you have written your questions, test them out on another group. Are your questions clear enough? If there are two possible answers you need to adapt the question to make it more clear.

PEER ASSESSMENT

When you exchange quizzes with another group, give them feedback on their questions. Rate questions 'green', 'amber' or 'red':

- green: great question
- amber: good idea but needs to be clearer
- red: do not use this question as it is misleading or contains wrong information.

For questions rated amber or red, you should also give written feedback.

After feedback and improvement work following the feedback, try your quiz out on some other students

Think about what you found most useful in this project. Was it researching and summarising? Maybe you enjoyed writing the questions, or the challenge of answering questions set by others. What does this tell you about how you like to learn? How will you apply this in your future revision?

SUMMARY

The Earth spins on its axis every 24 hours causing day and night.
The Earth is tilted on its axis. This causes the seasons as the Earth orbits the Sun every 365 days.
The Moon orbits the Earth every 27.5 days, causing the phases of the Moon.
The Sun is orbited by four rocky inner planets, four gaseous outer planets and minor planets, moons and comets.
All objects orbiting the Sun are kept in orbit by its gravitational attraction.
Light from the Sun takes approximately eight minutes to reach the Earth. The distances for sunlight to reach other planets can be calculated using the equation speed = distance/time.
The speed of an object in orbit can be calculated using the equation $v = \frac{2\pi r}{T}$ where r is the radius of the orbit and T is the orbital duration
The orbits of the planets are slightly elliptical. The Sun is not at the centre of the ellipse. Comets have highly elliptical orbits.
The Sun contains almost all of the mass of the Solar System and so has a very strong gravitational field
As distance from the Sun increases, its gravitational field strength decreases and the orbital speed of any orbiting object decreases.

CONTINUED

When an orbiting object is at its closest to the Sun, it has its maximum kinetic energy and minimum gravitational potential energy.

Planetary data about orbital distance, orbital duration, density, surface temperature and gravitational field strength can be analysed to show patterns in the properties and behaviour of the planets.

EXAM-STYLE QUESTIONS

1 Which of the following objects is a planet? [1]

A the Moon B Hale-Bopp C Pluto D Uranus

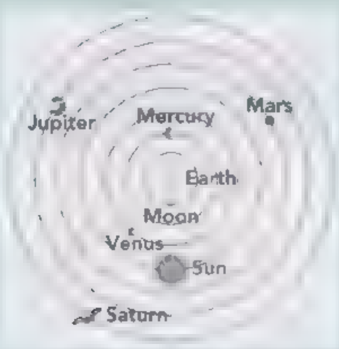
2 Which statement about the orbits of the Earth and Moon is correct? [1]

A The Moon rotates on its axis in 24 hours and orbits the Earth in 27.5 days.
B The Earth rotates on its axis in 24 hours and orbits the Sun in 365 days.
C The Moon orbits the Sun in 27.5 days.
D The Earth rotates on its axis in 24 hours and orbits the Moon in 27.5 days.

3 What force keeps the planets in orbit round the Sun? [1]

A momentum B air resistance C tension D gravity

4 The diagram shows how people 1000 years ago thought the Solar System looked.



a State **one** way in which this model is different from what we now know about the Solar System. [1]

b State **one** way in which this model is similar to what we now know about the Solar System. [1]

c State **one** way in which the planets Mercury, Venus, Earth and Mars are similar. [1]

d State **one** way in which Jupiter and Saturn are different to the planets in part c. [1]

e Mars is 228 million km from the Sun. Calculate the time it takes for light to travel from the Sun to Mars. The speed of light is 3×10^8 m/s. [3]

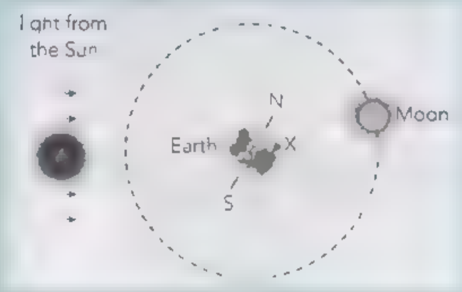
[Total: 7]

COMMAND WORDS

state: express in clear terms

calculate: work out from given facts, figures or information

5 Laurie is standing at point X on the Earth's surface.



a How can you tell it is night time at point X? [1]

b Redraw the diagram to show where point X will be after 12 hours. [1]

c The Moon does not emit light. **Explain** how Laurie is able to see the Moon. [1]

d Name the force which keeps the Moon in orbit around the Earth. [1]

e **Describe** the movement of the Moon. [2]

f A ball dropped on Earth will fall faster than an identical ball dropped on the Moon. What does this tell you about the Moon's gravity? [1]

[Total: 7]

Object	Distance from Sun / million km	Average surface temperature / °C	Density / kg/m³	Surface gravity / N/kg	Time of orbit / years
Venus	108	470	5200	9	0.6
Earth	150	15	5500	10	1.0
Mars	228	−30	4000	5	1.9
Jupiter	778	−150	1300	26	12
Saturn	1427	−180	700	11	30
Pluto	5900	230	500	4	248

[Total: 9]

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

describe: state the points of a topic; give characteristics and main features

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

Explain how the Earth's rotation on its axis causes day and night and the apparent change in position of the Sun	24.1			
Explain how the Earth's tilted axis and its rotation around the Sun cause seasons.	24.1			
Explain how the Moon orbiting the Earth leads to the different phases of the Moon	24.1			
State how long it takes for the Earth to rotate, for the Earth to orbit the Sun and for the Moon to orbit the Earth	24.1			
Name the different objects which orbit the Sun	24.2			
Explain the difference between the inner and outer planets	24.2			
Calculate the time it takes for light to travel from the Sun to a given planet.	24.2			
Name the force which keeps the planets in orbit	24.2			
Describe the shape of planetary orbits and state the position of the Sun within this shape	24.2			
Calculate orbital speed using the equation $v = \frac{2\pi r}{T}$	24.2			
Describe how gravitational potential energy and kinetic energy vary as an object moves in an elliptical orbit.	24.2			
Explain why the Sun has the largest gravitational field of any object in the Solar System.	24.2			
Interpret planetary data and describe patterns in this data.	24.2			

> Chapter 25

Stars and the Universe

IN THIS CHAPTER YOU WILL:

- describe the Sun and galaxies, including the Milky Way
- learn about the relative separation of planets, stars and galaxies
- [illegible]
- describe the life cycle of stars like our Sun and more massive stars
- learn that the redshift of light from distant galaxies supports the Big Bang theory
- [illegible] the Universe

GETTING STARTED

Spend two minutes thinking about these questions before comparing notes with your neighbour for a further two minutes, adding to or correcting your own work. Be prepared to share your thoughts with the class

- List the differences between planets and stars.
- Where does the Sun get its energy?
- What colour are stars?
- What is a galaxy and what is the name of our galaxy?
- List what you know about the Universe

WHAT MAKES THE SUN SHINE?

We know many things about the Sun but a lot of that knowledge has been gained very recently. Working out what makes the Sun shine was a process of eliminating different hypotheses (ideas) until one was found that best fits the evidence.

The Greek philosopher Aristotle believed the Sun was made of ether, a perfect substance that glows forever. However, in 1613, Galileo Galilei observed sunspots on the Sun and these 'imperfections' showed that the Sun could not be made of ether.

Coal was burned in steam engines to power the UK's Industrial Revolution. This made scientists wonder whether the Sun was a giant lump of coal but calculations showed that a Sun made of coal would shine for less than 1500 years and this is a shorter time than recorded history. However, efforts to understand steam power led to the principle of conservation of energy. This led scientists to look for other sources of energy (that could be transferred by light).

Scientists like Hermann von Helmholtz believed the kinetic energy of meteorites (lumps of rock) colliding with the Sun could be this source of energy. However, the total mass of meteorites was too small and they were not moving fast enough to provide the required energy.

Other scientists imagined that the Sun was once much bigger so that it only just fitted inside the Earth's orbit. But the gravitational energy released when it collapsed to its present size could only have provided enough energy for 100 million years, which was not enough time for the evolution of different species on Earth to have taken place.

Then radioactivity was discovered, and Einstein showed that mass can be transformed into energy. This led scientists to work out that the Sun is powered by thermonuclear fusion, though a fully formed theory did not appear until 1939.

Figure 25.1: The Sun shining.

Discussion questions

1 List at least three things that most people used to believe about what makes the Sun shine. For each one, write down how scientists showed that the belief was incorrect.

25.1 The Sun

The Sun is an average or medium mass star and is made up of about 75% hydrogen and about 24% helium. The rest (about 1%) is made up of other elements, such as oxygen and carbon.

The glowing hydrogen at the surface of the Sun radiates energy. About 40% of this energy is visible light, about 50% is infrared radiation, and the remaining 10% is ultraviolet. Earth's atmosphere absorbs a lot of this ultraviolet radiation. The ozone layer, in particular, absorbs most of the harmful (more ionising) ultraviolet.

Stars are powered by nuclear reactions that release energy. **Stable stars** like our Sun are powered by the nuclear fusion (or thermonuclear fusion) of hydrogen into helium. This makes the Sun shine. It is so hot inside the Sun that matter exists as **plasma** (positive ions and electrons). Although the Sun produces gamma rays because of the nuclear fusion process, collisions with the plasma mean that it takes about 100 000 years for that energy to reach the Sun's surface. In addition, because the energy is spread over a big surface (called the photosphere) the temperature is lower at the Sun's surface (about 5800 K compared to a core temperature of about 15 000 000 K).

The Earth orbits the Sun at a distance of about 150 million kilometres, which is within the habitable zone. This is the zone where water can exist in liquid form (an essential requirement for life as we know it). If it was hotter, the water vapour would never condense; if it was colder, ice would never melt.

The Sun has a mass of 2×10^{30} kg. This is referred to as the **solar mass** as it provides a simple way of comparing the mass of other stars to the mass of our Sun. For example, a star with eight solar masses would have eight times the mass of the Sun. The Sun contains over 99.86% of the mass of the Solar System so it exerts a big gravitational force on the planets and causes them to follow nearly circular orbits.

[illegible]

stable star: a star that is not collapsing or expanding because the inward force of gravity is balanced by radiation pressure, which pushes outwards

plasma: a completely ionised gas in which the temperature is too high for neutral atoms to exist so it consists of electrons and positively-charged atomic nuclei

solar mass: equal to the mass of the Sun (2×10^{30} kg)

Questions

1 From which two elements is the Sun mostly made?

2 Give an approximate value for:
  a the temperature in the Sun's core
  b the temperature of the Sun's surface
  c the solar mass
  d the percentage of sunlight that is in the infrared, visible and ultraviolet parts of the electromagnetic spectrum.

3 Name the process that makes stable stars, such as our Sun, shine.

4 Imagine that Earth orbited a star that gives off most of its energy in the ultraviolet region of the spectrum. Discuss whether our eyes would still have evolved to see visible light.

ACTIVITY 25.1

What colour is the Sun?

Spend two minutes writing down your thoughts and answers to the questions. Then spend one minute discussing them with a partner.

Your teacher may give you additional time to research these questions using the Internet, or ask supplementary questions to help you reach the correct answer.

1 Why do most people think the Sun is yellow?

2 Is this the correct colour of the Sun? How do we know?

Did you already know the correct answer to Activity 25.1?

It s important in science to avoid looking for evidence that supports an idea that you already th nk is correct. Scientists must also avoid not looking for evidence at all and assuming that they already know the answer. If you thought the Sun is yellow, did you question this idea? If you guessed that the Sun is not yellow, did you know what questions to ask to work out its correct colour?

Were you able to think objectively and find evidence to support the correct answer? This is how science progresses and it is the approach outlined in the Science in context section What makes the Sun shine? that led to correctly understanding how stars shine.

25.2 Stars and galaxies

When you look into the night sky, the light that you see from the stars has been travelling for many years. Astronomers use this idea as a way of measuring vast distances. A **light-year** is a measure of distance (not time). It is the distance that light travels through space in one year. Light travels at a constant speed of 3×10^8 m/s through a vacuum. This means that the time it takes to travel somewhere is directly proportional to distance.

One light-year is the distance that light travels in one year

distance = speed × time

So, one light-year = 3×10^8 m/s × 365.25 days × 24 hours × 3600 seconds = 9.5×10^{15} m

light-year: the distance travelled in space by light in one year (it is equivalent to about 9.5×10^{15} m)

The distance between stars is much bigger than the size of each solar system. After the Sun, our next nearest star is Proxima Centauri, which is about 4.2 light-years away. When you see Proxima Centauri the light left it 4.2 years ago; sunlight only takes eight minutes to reach us because the Sun is much closer to us. Pluto has an elliptical orbit but, on average, it is 40 times further from the Sun than the Earth is. But this is dwarfed by the distance between Proxima Centauri and the Sun, which is 7000 times further from the Sun than Pluto is.

Questions

5 The Sun is about eight light-minutes away. It takes sunlight about eight minutes to reach Earth on its journey from the Sun.

a Given that the speed of light is 3×10^8 m/s, how far away is the Sun in kilometres?

b How many years would it take a car to get to the Sun travelling at 120 km/h?

6 After our Sun, Proxima Centauri is our next nearest star. It is about 4.2 light-years away.

a How many seconds does it take light from Proxima Centauri to reach Earth?

b How far away is Proxima Centauri in km?

c Helios I & II hold the record as the fastest ever space probes at 252 738 km/h (about 70 km/s). How many years would it take these space probes to reach Proxima Centauri?

d How long would it take them to reach the nearest galaxy 25 000 light-years away from us?

The force of gravity pulls stars together in groups called galaxies. Our Sun is one of many billions of stars in our galaxy, the Milky Way. There might be 200 billion (2×10^{11}) stars in the Milky Way, about 20 stars for every person on Earth. The Milky Way is a spiral galaxy with a central bulge (see Figure 25.2). It has a diameter of 100 000 light-years and the disc is about 2000 light-years thick. Our Solar System is located about 30 000 light-years from the galactic centre, two-thirds of the way along a spiral arm. The Milky Way is spinning and it takes our Solar System about 225 million years to travel once around the galaxy.

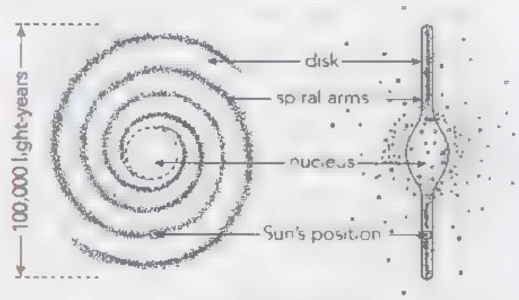


Figure 25.2: A schematic diagram of the Milky Way Galaxy

The Milky Way is one of many billions of galaxies, that make up the Universe. Most people consider the Andromeda Galaxy (Figure 25.3) to be our closest galactic neighbour and it is certainly our closest spiral galaxy. However, our nearest galactic neighbour is the Canis Major

Dwarf Galaxy, which is 25 000 light-years away from us and 42 000 light-years from the centre of the Milky Way.

Figure 25.3: An infrared image of the Andromeda Galaxy, our closest spiral galaxy

Questions

7 a Make two sketches to show the Milky Way Galaxy; one sketch should show its spiral structure and the other should show the galaxy edge on.

b On your sketches mark the diameter of the Milky Way in light-years.

c Mark the position of the Sun in the Milky Way.

d How many stars are there in the Milky Way?

8 The Solar System has existed for 4.6 billion years. How many times has the Solar System travelled around the Milky Way in that time?

9 How can the Canis Major Dwarf Galaxy be closer to us than we are to the centre of our own galaxy?

10 Assuming that the average mass of a star is equal to the mass of the Sun (2×10^{30} kg), what is the mass of the Milky Way?

11 Imagine that the Milky Way is shrunk down to fit into the space between the Earth and the Sun. On this scale, calculate how far away the following bodies would be from Earth.

a Proxima Centauri (in km)

b Pluto (in km)

c the Sun (in metres)

d the Moon (in cm)

12 Write a sentence or two comparing your answers to question 25.11 with the length of a pencil, the length of a cricket pitch (about 20 metres), a 400 metre athletics track, and the radius of the Earth (6400 km).

How do astronomers measure distances to faraway objects?

Astronomers have many techniques to measure distances in space. For nearby stars within our own galaxy, they can use parallax. This is when the star appears to move across the sky when viewed from opposite sides of our orbit around the Sun, as shown in Figure 25.4.

You can experience this yourself. Stretch out an arm in front of you and stick up your thumb. Close one eye and open the other and then swap over which is closed and open. Your thumb should appear to move from side to side against the background (which should be at least two arm lengths away).

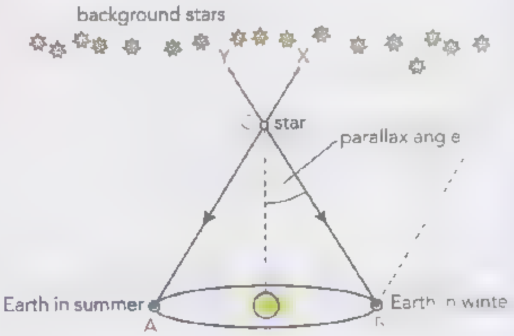


Figure 25.4: Parallax in nearby stars

When a telescope is pointed at a nearby star in the summer it appears to be at location X against the background stars. When the telescope is pointed in the same direction six months later (shown by the dashed line from B), the astronomer would need to swing the telescope through twice the parallax angle in order to get the telescope back onto the star, which appears to have moved to position Y against the background stars.

1 In groups, use the biggest space available to you to mark out three positions to represent the locations of the Earth in summer (A), the Earth in winter (B), and distant star (C), located roughly south of A and B. Ensure that the distant star is on the perpendicular bisector of the line joining A and B. Measure the distance between the Sun and the star.

2 Measure the distance between A and B. Compass apps are standard on mobile phones. Stand at position A and use the app to measure the angle to C. Then move to B and measure the angle to C. Subtract the two angles and divide by two to get the parallax angle. Use trigonometry or a scale drawing to find the distance between the Sun and the star. Check whether your answer is within 10% of the distance measured. If your answer is incorrect, identify the source of the error.

3 Repeat step 2 with the layout produced by other groups but keep the distance to your 'star' a secret until the end. The winning group is the one that gets consistently closest to the actual value.

A protostar – how a star is born

A **protostar** is the first step in star formation. Stars form from **interstellar clouds** of gas and dust that contain hydrogen called **molecular clouds**, which are both cold and dense enough for star formation. The Orion Nebula (Figure 25.5) in the Milky Way is about 1350 light-years away and it is the closest region of star formation to us. It is visible to the naked eye in the night sky just south of Orion's Belt in the constellation of Orion.

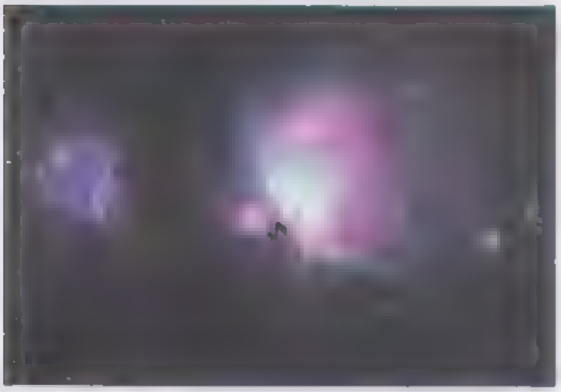


Figure 25.5: The Orion Nebula, the closest region of star formation and visible to the naked eye.

The collapse of a clump of molecular cloud due to gravitational attraction starts a series of energy transfers. As the force of gravity pulls the hydrogen gas molecules closer together, their gravitational potential energy is transferred to kinetic energy. As the molecules collide, their kinetic energy is transferred into thermal energy. The clump contracts into a spinning sphere of super-hot gas known as a protostar. A protostar continues to grow by pulling in more material from the molecular cloud. Its final mass determines what happens to it. A protostar becomes stable when the inward force of gravitational attraction is balanced by an outward force due to the high temperature of a star caused by nuclear fusion.

protostar: a very young star that is still gathering mass from its parent molecular cloud

interstellar cloud: a cloud of gas and dust that occupies the space between stars

molecular cloud: a cloud of interstellar gas that consists mostly of molecular hydrogen and is cold and dense enough to collapse to form stars

Questions

13 What two properties do molecular clouds have that allow them to collapse?

14 a Explain how stars are formed.

b What causes the centre of a star to warm up when it forms?

15 a Explain what is meant by nuclear fusion.

b Why can nuclear fusion only occur at high temperatures?

Stable stars

Hot bodies radiate heat and this radiation exerts a force called **radiation pressure**. The hotter the object is, the higher the radiation pressure. The very high temperature of a star leads to a radiation pressure that acts outwards, making the star expand. This acts in the opposite direction to the force of gravity pulling the star inwards, making the star contract. When these forces are balanced, the star is stable and stays the same size as shown in Figure 25.6. An increase in the core temperature of a star increases the radiation pressure and the star increases in size. A star shrinks when its core temperature falls.

radiation pressure: the outward force due to the high temperature of the star

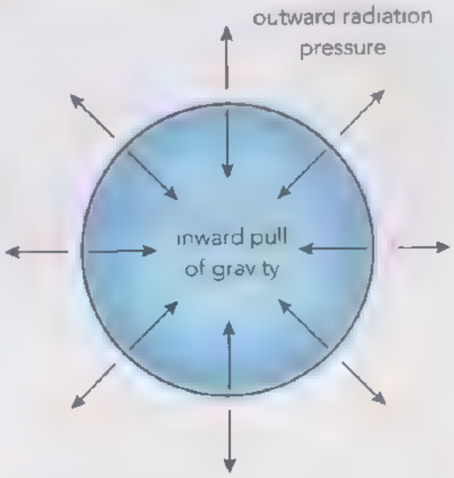


Figure 25.6: A star is stable when the inward pull of gravity is balanced by the outward push of radiation pressure, which is actually a force.

The life cycle of a less massive star like our Sun

Like all stars, it begins life as a protostar before a entering a stable period. Once the star starts running out of hydrogen, nuclear reactions slow down. This reduces the radiation pressure so the star contracts. This turns some gravitational potential energy into thermal energy, which raises the temperature of both the core of the star and the outer shell of hydrogen. The core becomes hot enough for the fusion of helium. Helium needs a higher temperature to fuse because there is a bigger electrostatic repulsion between the helium nuclei. This is because each helium nucleus has a charge of +2 (instead of +1 for hydrogen). Heating the outer shell causes it to expand and then cool (turning it red). Therefore, the star becomes a red giant, which is a bigger star with a cooler surface.

Our Sun is 4.6 billion years old and is half-way through its time as a stable main sequence star. It will become a red giant in about 5 billion years from now when it will expand beyond Earth's orbit. Eventually, the core collapses into a white dwarf star. A white dwarf cannot exceed a mass of about 1.4 solar masses and typically has a radius of 1000 km. When the Sun becomes a white dwarf, its radius will be about 1% of its present radius which means it will shrink to about the size of the Earth. Though it has a white hot surface (hence the colour), it is not hot enough inside to fuse heavier elements, so it will cool to become a black dwarf. Radiation pressure blows away its outer shell to create a planetary nebula like the Cat's Eye Nebula (Figure 25.7).

red giant: a star that began with fewer than eight solar masses and is burning helium in its core; its shell of hydrogen has expanded and cooled

main sequence: a stable star that is burning hydrogen in its core; once it has used up 12% of its hydrogen it goes onto another stage of its life cycle

white dwarf: the final stage of a star that started with fewer than eight solar masses after all its fuel has been used up

planetary nebula: a bubble of gas surrounding a white dwarf star that used to be the outer shell of a red giant from which it collapsed

Figure 25.7: The planetary nebula NGC 6543, known as the Cat's Eye Nebula, taken from the Hubble Space Telescope. The white dot in the middle is a white dwarf star, which is what our Sun will become in about 5 billion years.

The life cycle of a star exceeding eight solar masses

Like all stars, it begins life as a protostar before a entering a stable period The core of more massive stars gets so hot that the nuclei of heavier elements can fuse. The star is hot enough for the fusion of lighter elements to continue in shells further from the core, as shown in Figure 25.8. The outer shell expands into a red supergiant. However, it is not possible to make elements heavier than iron by nuclear fusion so a star with at least eight times the mass of the Sun ends its cycle of nuclear reactions with iron at its core surrounded by shells of progressively lighter elements.

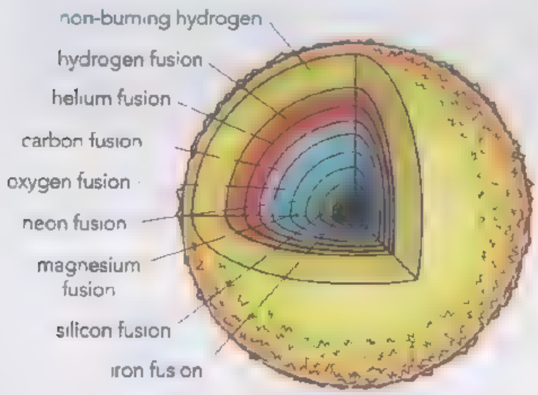


Figure 25.8: More massive stars have shells of different elements, with the heavier elements falling towards the core.

Once all the fuel has run out, the star collapses one final time and then explodes as a supernova This provides the energy required to create elements heavier than iron and push them into space as a nebula, along with lighter elements (including hydrogen) The nebula provides the building blocks for possible future stars and solar systems. A supernova will briefly outshine its galaxy. The Crab Nebula (Figure 25.9) is what remains of a supernova observed by Chinese astronomers in 1054 What happens after a supernova depends on the mass of the core that remains. If the core is less than about three solar masses, a neutron star forms. The force of gravity is so strong that electrons and protons are forced together to create neutrons. An even more massive core will continue collapsing until it becomes so dense that not even light can escape and the star becomes a black hole

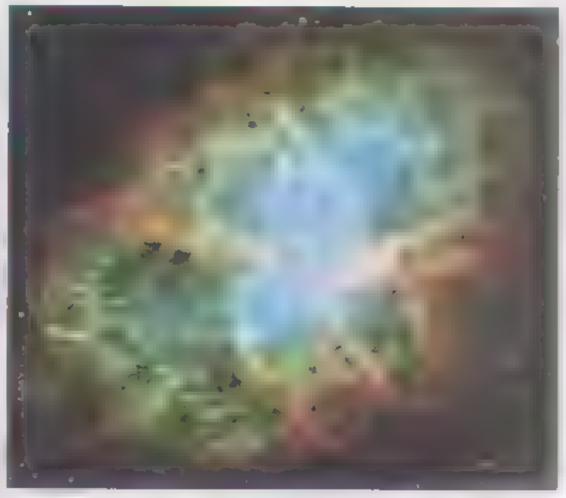


Figure 25.9: A supernova in 1054 left behind the Crab Nebula and a neutron star somewhere within

red supergiant: similar to red giants, they form when stars with at least eight times the mass of the Sun run out of hydrogen fuel in their core but fusion of hydrogen continues in the outer shells

supernova an exploding star that began life with more than eight solar masses and has run out of fuel

neutron star: a collapsed s[illegible] composed almost entirely of neutrons which for[illegible] more than eight solar mas[illegible] its life

black hole: the final stage in the life cycle [illegible] a star that started with more than eight solar masses, it has enough mass left over after exploding as a supernova to collapse to a point where gravity is so strong that not even light can escape

The possible life cycles of stars is summarised in Figure 25.10 All stars begin as a protostar but the future path of a star is determined by its mass when it moves onto the main sequence, a stage in its life when it is stable and burning hydrogen Stars that are more massive spend less time on the main sequence as they have a higher core temperature and use up their fuel more quickly

Figure 25.10 The life cycle of a star depends on its initial (starting) mass. All stars begin as protostars in molecular clouds before joining the main sequence. Stars with a starting mass of fewer than eight solar masses follow the top row while heavier stars move along the bottom row and explode as supernovae. After the supernova stage, the lighter stars become neutron stars while the rest become black holes.

The Big Bang created hydrogen, helium and a trace of lithium, so stars have produced the rest. This means the Solar System contains stardust. The Sun is a third generation star, which means that it includes matter that has been through two previous stars, including one that ended in a supernova explosion. In fact, we may have atoms in our bodies that come from many stars because supernova explosions mix up matter in the interstellar medium.

Questions

16 Explain the following terms about the life cycle of a star

- a protostar
- b main sequence star
- c red giant
- d white dwarf
- e supernova
- f neutron star
- g black hole

17 Construct a flow chart to show how the stages listed in question 25.16 fit together in the life cycle of stars

25.3 The Universe

The Universe has only recently been discovered: on New Year's Day, 1925. This is when Edwin Hubble's scientific paper was presented that ended the 'Great Debate' and proved that the Universe is bigger than the Milky Way. Astronomers had observed what looked like whirlpools of gas and dust inside our galaxy. But when Hubble focused the new Mount Palomar telescope onto them he realised they were other galaxies beyond our own. Along with 53 other galaxies and dwarf galaxies, we are part of the local group of galaxies, which is part of the Virgo Supercluster.

Spectroscopy – learning about stars from their starlight

It is remarkable what starlight can tell us about a star. Spectroscopy, or the scientific study of spectra, began with Isaac Newton in 1666. He discovered that a prism (a triangular block of glass) disperses white light into the colours of the visible spectrum as covered in Chapter 13.

In 1814, Joseph Fraunhofer noticed that many dark lines cross the spectrum of sunlight. These dark lines are the wavelengths of light missing from the sunlight because

the cool gas in the Sun's atmosphere absorbs them. A spectrum with these absorption lines is known as an **absorption spectrum** (see Figure 25.11). For reasons that are beyond this course, each element has a unique set of lines (sometimes known as a spectral fingerprint) similar to a barcode. These lines allow astronomers to work out what elements are inside a star

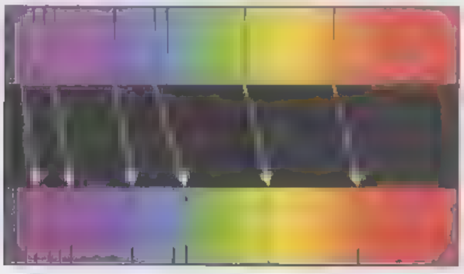


Figure 25.11a: An absorption spectrum found in an experiment on Earth. **b:** The redshifted spectrum observed from a distant galaxy

The spectrum for hydrogen and other elements has been found in experiments on Earth. However, when astronomers looked for the same spectra in distant galaxies, they discovered that they are **redshifted** (shifted towards the red end of the spectrum).

This does not mean that electromagnetic radiation (including visible light) from distant galaxies turns red. It means light shifts towards longer wavelengths because the wave is stretched out and the wavelength is increased. For example, as can be seen in Figure 25.11, absorption lines that are normally in the blue part of the spectrum can shift into the green part of the spectrum.

KEY WORDS

absorption spectrum: dark lines in a spectrum that are produced when light passing through cooler gas is absorbed

redshift: an increase in the observed wavelength of electromagnetic radiation (including visible light) from a star or galaxy because it is moving away from us

The Doppler effect

You may already have noticed the Doppler effect. As a very fast vehicle passes you, the volume of the sound rises and falls. However, the pitch also increases as the vehicle approaches and decreases as it recedes (moves away). The sound wave is compressed in front of the vehicle as it approaches. This is because once the crest (or compression) of a sound wave leaves the car, the car catches up with it before the next crest of the wave leaves the car, as shown in Figure 25.12. The sound wave is stretched out behind the vehicle as it moves away.

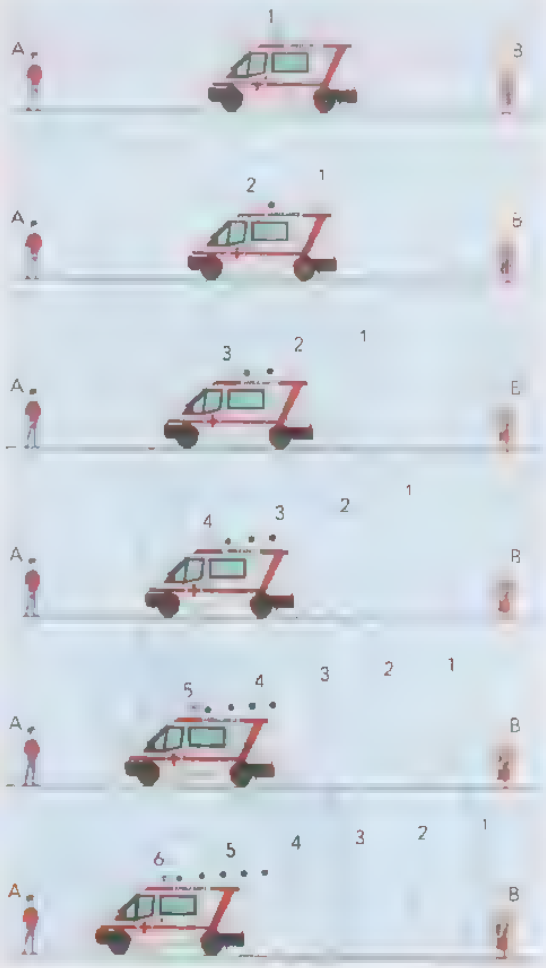


Figure 25.12: This diagram shows crests of a sound wave modified by the Doppler effect, with the wave compressed ahead of the ambulance (so person A hears a higher pitch) and redshifted behind (so person B hears a lower pitch) By the time it emits the next crest, the ambulance has moved forward, closing the gap on the previous crest

The Doppler effect is a property of all waves, including light. Light from galaxies that are moving away from us is redshifted. This turned out to be the first important clue that the Universe is expanding and suggested that the galaxies must have been closer together in the past. This led to the theory that the Universe had a beginning: the Big Bang theory. This is the idea that the Universe (space, time, matter, energy) was created at a single point 13.8 billion years ago and has been expanding and cooling ever since.

Big Bang theory the Universe (space, time, matter, energy) was created at a single point 13.8 billion years ago and has been expanding and cooling ever since

Hubble's law

Astronomers use the Doppler effect to work out how fast galaxies are moving away from us (or towards us). The speed of the galaxies is directly proportional to the amount of redshift. In 1921, Edwin Hubble plotted the recession speed of galaxies (how fast they are moving away) against their distance from us. He got a graph like Figure 25.13. It shows that the speed at which galaxies are moving away from us is directly proportional to their distance from us.

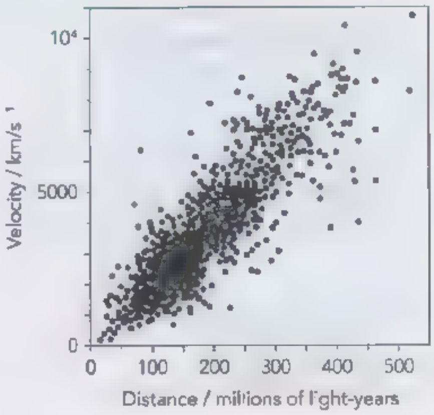


Figure 25.13: A typical Hubble plot that shows that the velocity of galaxies and clusters is directly proportional to their distance from us.

His line of best fit is Hubble's law:

$$v = H_0 d$$

Here, v is the recession speed of galaxies (how fast they are moving away from us) and d is their distance from us. The graph confirms that the further away the galaxy is, the faster it is moving away from us.

The Hubble constant, is the gradient of this graph and it is the ratio of the speed at which galaxies are moving away from Earth to their distance from Earth:

$$H_0 = \frac{v}{d}$$

Hubble constant = $\frac{\text{speed of galaxy moving away from Earth}}{\text{distance of the galaxy from Earth}}$

$$H_0 = \frac{v}{d}$$

Estimate for the age of the Universe

$$\frac{d}{v} = \frac{1}{H_0}$$

The current estimate for H_0 is 2.2×10^{-18} per second

The reciprocal (inverse) of the Hubble constant is known as Hubble time because it can be used to work out the age of the Universe. From the equation that links distance, speed and time, we know that:

$$\text{time} = \frac{\text{distance}}{\text{speed}}$$

So:

$$t_{\text{universe}} = \frac{d}{v} = \frac{1}{H_0}$$

Therefore, the age of the Universe is:

$$t_{\text{universe}} = \frac{1}{H_0} = \frac{1}{2.2 \times 10^{-18}} = 4.5 \times 10^{17}\ \text{s}$$

$$= 14.4 \times 10^9 \text{ years}$$

The Universe began at a single point (called a singularity) about 14.5 billion years ago.

KEY WORDS

Hubble's law: distant galaxies are moving away from Earth with a speed, v, that is proportional to their distance, d, from Earth; $v = H_0 d$ where H_0 is the Hubble constant

Hubble constant: the slope of a graph of galaxy speed against distance

Hubble time: the inverse of the Hubble constant, which gives an estimate for the age of the Universe

Questions

18 This question is about the Doppler effect. Use a compass to draw a circle of radius 5 cm. Then move the point of the compass 0.5 cm to the left and draw a circle of radius 4 cm. Repeat the process, moving the compass to the left and reducing the radius of the circle by 1 cm, until you have a nest of circles that are closer together on the left-hand side than the other. They represent circular sound waves produced by the engine of a racing car, at a scale of 1 cm = 1 metre.

- **a** What is the wavelength of the sound when the racing car is not moving?
- **b** What is the wavelength of the sound:
  - **i** ahead of the racing car?
  - **ii** behind the racing car?
- **c** Sound travels at 330 m/s. What is the frequency of the sound heard:
  - **i** ahead of the racing car?
  - **ii** behind the racing car?
  - **iii** if the racing car is not moving?
- **d** Explain what you would hear as the racing car passes you. Why does the car have to be travelling fast?

19 Figure 25.14 is a plot of the recession speed of superclusters against their distance from Earth.

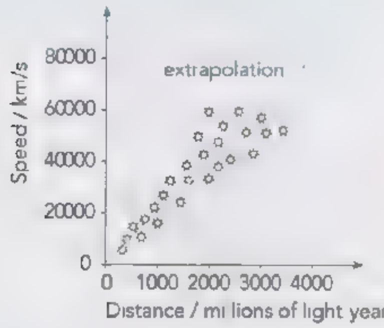


Figure 25.14: Recession speed of superclusters plotted against distance.

- **a** Use Figure 25.14 to calculate the Hubble constant, expressed
  - **i** in km/s per million light-years
  - **ii** per second. (Hint: it will help to recall that 1 light-year = 9.5×10^{12} km.)
- **b** **i** The redshift of the Saraswati Supercluster suggests that it is receding (moving away) from us at a speed of 84 000 km/s. Use the value of the Hubble constant you worked out in part **a i** to work out how far away the supercluster is from us and plot its position on a sketched copy of Figure 25.14.
  - **ii** Use your answer to part **a ii** to work out the age of the Universe.

The discovery of the cosmic microwave background radiation (CMBR)

Most cultures have a creation myth about how the Universe began. Science has only been able to offer an alternative explanation during the last century and many puzzles remain. Our best knowledge at the moment is that the Universe began as a hot big bang from a tiny point smaller than a pinhead (called a singularity) about 13.8 billion years ago. The Universe was unimaginably hot and dense but it has been expanding and cooling ever since. The early Universe was so hot that neutral atoms could not form. They would instantly ionise. Light was continuously scattered off the charged particles (ions and electrons). By analogy, light is scattered in fog, which is why you cannot see very far into it. Once the Universe was about 379 000 years old, and about the size of the Milky Way, the temperature dropped to 3000 K and neutral atoms formed. Light was no longer scattered and the Universe became transparent. It was like the fog suddenly lifted (disappeared) and the air became clear. However, the continued expansion of the Universe has caused the wavelength of this light to redshift over time.

The wavelength of this light, in the microwave region of the electromagnetic spectrum, was predicted in 1948. In 1964, the US scientists Arno Penzias and Robert Wilson (Figure 25.15) built a radio telescope but struggled to eliminate noise (unwanted signal). It did not matter where in the sky they pointed their telescope, the noise was constant, and so they assumed that it was a problem with their equipment. However, it turned out that they had accidentally discovered microwave radiation. They were looking at light that had left the surface of last scattering when the universe was only 379 000 years old (almost 14 billion years ago) and had been redshifted so that its wavelength was now more than 1000 times longer. This microwave radiation, called cosmic microwave background radiation (CMBR), has a temperature of 2.726 K (Figure 25.16). Penzias and Wilson were awarded the Nobel Prize for physics in 1978 for their accidental discovery.

Figure 25.15: Robert Wilson and Arno Penzias in front of the radio telescope that detected the cosmic microwave background radiation

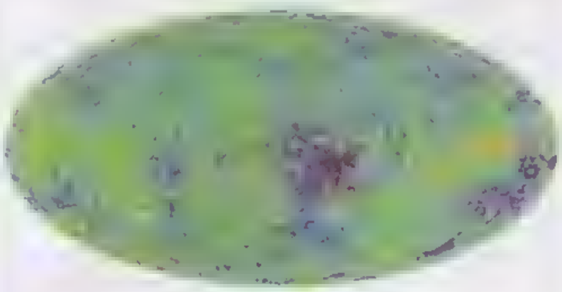


Figure 25.16: Full sky map of cosmic microwave background radiation. This is the radiation emitted when the Universe was 379 000 years old but redshifted into the microwave region of the electromagnetic spectrum. This shows that the Universe has a uniform temperature of 2.726 K in all directions, with only very tiny variations, indicated by the false colours

Despite the name, the Big Bang was not an explosion. It is the expansion of the space between the galaxies. Imagine your universe is the two-dimensional surface of a balloon. Everything inside or outside of the balloon does not exist. As space expands (that is, the balloon inflates), clusters of galaxies move further apart with their recession speeds increasing with distance as shown in Figure 25.17. No matter the direction we look, galaxies appear to be moving away from us, suggesting we are at the centre of the Universe. However, aliens on a distant galaxy would also think they were at the centre of the Universe, with all other galaxies moving away from them. Actually, the Universe does not have a centre or an edge. Do not worry if you find this idea impossible to imagine because nobody can. The best we can do is to present models.

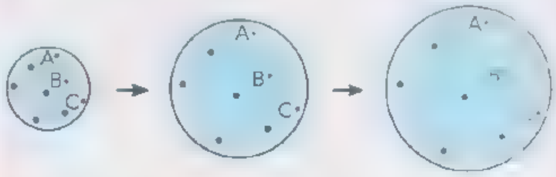


Figure 25.17: The Universe represented by the surface of an expanding balloon.

ACTIVITY 25.3

Using Hubble's law to find the centre of the Universe

Work individually, in pairs, or in groups (four would be ideal) on this task. If you have a strip of elastic with buttons sewn into it, you can do this as an experiment under the guidance of your teacher. You need to stretch the elastic by the same amount for each 'time interval' so that it looks something like Figure 25.18. If buttons and elastic are not available, take measurements from the diagram.

Each button represents a cluster of galaxies. Cluster A represents the local group (where the Milky Way Galaxy is located). The scale is 3 mm = 10 million light-years.

1. Measure the distances between the centres of the clusters and record them on a copy the Table 25.1a. Compare your measurements with other students and reach a consensus (agreement). Check that the value in the final column for each row is equal to the sum of the three previous columns.
2. If you are working in a group then each of you should take one of the clusters and work out the distance to all the other clusters, using the distances you agreed in the previous step. For example, if you are allocated cluster (button) C, you will be a scientist looking at the expanding universe as if you were living on a planet in cluster C and working out the distances to clusters B, A and D. Do this for all the different times and complete your own table, which should look something like the one in Table 25.1b.

CONTINUED

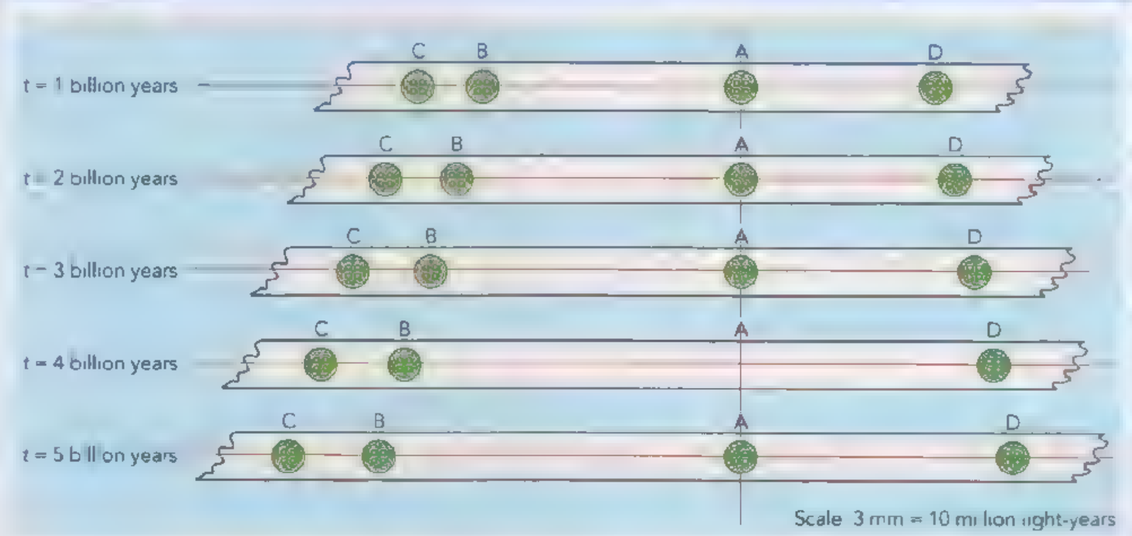


Figure 25.18: Modelling the expanding Universe

Time (billion years)	C-B	B-A	A-D	Total (C-D)
1				
2				
3				
4				
5				

Table 25.1a: Agreed distances between clusters

Time (billion years)	Distance to B	Distance to A	Distance to D
1			
2			
3			
4			
5			

Table 25.1b: Example table (for cluster C)

3 For your allocated cluster, plot a graph of distance (in millions of light-years) against time (in billions of years) to the other three clusters. It will save time and make it easier to compare if you plot all three graphs on the same axes but ensure you label each graph with the correct letter for each cluster.

4 Use your plotted distance-time graph(s) from the previous step to work out the (recession) speed for each cluster (in million light-years per billion years) and comment on what you find. Sketch a graph of speed against original distance. How do you interpret your results?

5 Compare what you find with your classmates. Check that the recession speed is the same for pairs of galaxies. For example, the speed of B as seen from D should be the same as the speed of D as seen from B.

PEER ASSESSMENT

Look at the work of fellow students who have completed this task (your teammates if you have been working in a group of four).

- Which piece of work is the most accurate and easiest to follow? If you had been absent and missed this lesson whose work would you want to read to help you understand the missed work?
- Identify the reasons why this work stands out but also how it could be improved.
- In your group make a list of things that everyone can do to set out their work more clearly.
- Your teacher may ask your group to discuss the piece of work you have chosen.

Question

20 Describe in detail two pieces of evidence that support the Big Bang theory.

Measuring distances with supernovae

Having found evidence that the Universe is expanding, scientists are now asking what will happen to the Universe in the future. Observations in 1998 of type 1a supernovae in a very distant galaxy suggest that the expansion of the Universe is accelerating. Type 1a supernovae occur when a white dwarf star in a binary star system (when two stars orbit each other) pulls in material from its companion star until it reaches a certain mass and then explodes. The important point is that these supernovae always have the same luminosity (output power) therefore they act as a 'standard candle'. By recording how bright the supernova appears to be and knowing how bright it really is, it is possible to work out how far away it is. Scientists are still not able to explain why the expansion of the Universe is speeding up, but they have suggested that something called 'dark energy' is responsible. If you continue to study physics you will learn more about this.

PROJECT

Are we alone in the Universe?

The possibility of life elsewhere in the Universe fascinates and frightens people in equal measure and is the subject of many science fiction stories, both in books and movies. Science fiction (as opposed to fantasy) often works better if the underlying science is correct or, at least, possible.

When looking for life beyond Earth, it is important to consider what conditions are required for life on Earth. We need liquid water (as a solvent for the chemical reactions needed for life), a source of energy (we depend on sunlight), and chemical building blocks. Scientists have discovered that most stars have solar systems of orbiting planets, increasing the chances that the conditions for life on Earth exist on other planets, beyond the Solar System.

However, liquid water is not the only possible solvent for chemical reactions. Ammonia and liquid hydrocarbons (like methane) are alternatives and have raised hopes of finding life on Titan, the largest moon orbiting Saturn.

Sunlight is not the only source of energy. In 1977, hydrothermal vents (called black smokers) were discovered at mid-ocean ridges several kilometres below the ocean surface. Even though they are far deeper than light can reach, ecosystems have formed around them. These ecosystems get their energy from the chemical reaction between oxygen and hydrogen sulphide. This has increased hopes of finding life beneath the ice of Europa, one of Jupiter's moons. Microbes have also been discovered deep underground in the Earth's crust.

Life on Earth is based on carbon, which can bond with to up four other atoms and forms more compounds than all other elements combined. However, life could also be based on silicon, which is in the same group in the Periodic Table and can also form a huge variety of compounds.

You have two tasks.

1 Use the Internet to find more information on one of the following:

- The search for Earth-like extrasolar planets (planets in other solar systems that match the conditions required for life on Earth): you will find there are many other requirements for more complicated life forms (for example, the spin of the planet has to be stable). You can probably think of more before going online.
- The search for life within our Solar System: you could look at, for example, Mars, Europa or Titan.

2 Use the information presented here or the information you have found on the Internet to complete a short piece of creative science fiction writing, based on scientific fact. Aim for a maximum of 800 words (or what your teacher suggests). Use your imagination, but make sure that your story is concise and the science is clear and correct.

SUMMARY

Our Sun is an average star and is made mainly of hydrogen and helium.
Stable stars shine because of the thermonuclear fusion of hydrogen.
The Sun shines in the infrared and ultraviolet as well as the visible light.
A light-year is the distance that light travels in one year.
A light-year is defined as 9.5×10^{15} metres.
The Sun is of one of many billions of stars in our Milky Way Galaxy.
The distance between stars is thousands of times bigger than the distance between a star and planets in its solar system, if it has one.
Our Milky Way Galaxy is one of billions of others in the Universe.
Our nearest galaxy is more than 25 000 light-years from Earth. So, galaxies are much further apart than stars, and stars are much further apart than planets.
All stars begin as protostars from the collapse of interstellar (molecular) gas clouds and then start using hydrogen as their fuel.
A stable star uses hydrogen as its fuel and the outward force of radiation pressure due to its high temperature balances the inward force of gravity.
Low mass stars (less than eight times the mass of the Sun) swell into red giants when they run out of hydrogen fuel for their nuclear reactions.
When red giants run out of helium, they form a planetary nebula and shrink into white dwarfs.
High mass stars (more than eight times the mass of the Sun) will explode as supernovae that create elements heavier than iron and send this material into the interstellar medium as a nebulae that form the raw material for new stars and solar systems.
A star that explodes as a supernova collapses to become a neutron star or, if it has a bigger mass, a black hole.
Redshift is the increase in the wavelength of electromagnetic radiation (including visible light)

CONTINUED

Light from distant stars and galaxies is redshifted which suggests that they are moving away from us.
The fact that galaxies are moving away from us suggests that the Universe is expanding and supports the Big Bang theory.
The speed that a galaxy appears to be moving away from us can be found from the redshift in the starlight
The Hubble equation describes how the speed of galaxies is proportional to their distance from us.
The reciprocal of the Hubble constant tells us the age of the Universe
The cosmic microwave background radiation (CMBR) is electromagnetic radiation from the early Universe that has been redshifted and its wavelength stretched into the microwave region of the electromagnetic spectrum
The distance to a distant galaxy can be determined by the brightness of a type Ia supernova

[illegible]

1 Why do stars shine? [1]

A They are burning.

B Nuclear fusion is taking place inside the star

C They are made of hot gases that are heated up when they collapsed from gas clouds.

D They are made of ether.

2 What is a light-year? [1]

A the distance light travels in one year

B 366 days

C the time it takes light to travel in one year

D $1.44 \times 10^{[illegible]}$ metres

3 Which of the following is not a star? [1]

A neutron star

B white dwarf

C supernova

D red giant

4 Which of the following is not evidence of the Big Bang? [1]

A cosmic microwave background radiation everywhere

B galaxies are moving closer together

C stars that are redshifted

D the Universe is expanding

5 **a** What do we call a large group of stars? [1]

b Why do these groups form? [1]

c What is the name of the group where we live? [1]

d How many other groups of stars do we think exist in the Universe? [1]

[Total: 4]

6 a What causes the redshift in the light arriving from distant galaxies? [2]

Distance (million light-years)	Velocity (km/s)
0.0	0
1.6	270
2.3	360
3.0	470
1.7	890
5.6	990
6.6	1050
7.3	1150

b The table shows data for a parallel universe. Plot a graph of recessional speed (in km/s) versus distance (million light-years) to each galaxy for this parallel universe. [3]

[Total: 9]

8 What is the Big Bang theory and what evidence is there to support it? [3]

describe: state the points of a topic; give characteristics and main features

[illegible]

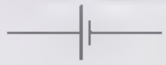
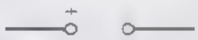
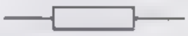
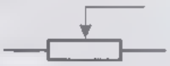
After studying this chapter think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively

[illegible]	[illegible] Topic [illegible]	[illegible]	[illegible]	[illegible]
Describe what the Sun is made of.	25.1			
Recall what parts of the electromagnetic spectrum are emitted by the Sun.	25.1			
Describe what powers a stable star.	25.1			
Recall the relative distances between planets, stars and galaxies.	25.2			
Recall what a light-year is.	25.2			
Define a light-year.	25.2			
Describe how a protostar is formed and how it becomes a stable star.	25.2			
Describe the life cycle of a star like the Sun, including the names of the different stages.	25.2			
Describe the life cycle of stars exceeding eight solar masses, including the names of the different stages.	25.2			
Describe the role of supernovae in creating heavy elements and spreading them.	25.2			
Recall the number of stars in the Milky Way and the number of galaxies in the Universe.	25.2			
Recall what redshift is.	25.3			
Recall how the redshift of electromagnetic radiation from distant stars and galaxies supports the Big Bang theory.	25.3			
Know that the redshift of light from distant galaxies can be used to work out their speed of recession (how fast they are moving away from us).	25.3			
Recall Hubble's Law and use it to work out the age of the Universe.	25.3			
Recall where to find the CMBR (cosmic microwave background radiation) and describe its origin (how it came into existence).	25.3			
Describe how the distance to a galaxy can be determined using a type 1a supernova.	25.3			

Appendix

Electrical symbols

You'll need to know the following electrical symbols for the 'Electricity and magnetism' section of the syllabus. The symbols highlighted in blue are supplement content

cell	
battery of cells	 or 
power supply	
d.c. power supply	
a.c. power supply	
fixed resistor	
variable resistor	
thermistor	
light-dependent resisitor	
heater	
potential divider	
magnetising coil	
transformer	
switch	
earth or ground	
junction of conductors	
lamp	
motor	
generator	
ammeter	
voltmeter	
diode	
light-emitting diode	
fuse	
relay coil	

Symbols

You'll need to know the usual scientific symbols for a number of physical quantities and, where relevant, the units that they're measured in The tables below show you what you need to know for the Core and Supplement options of the syllabus.

Core		
Quantity	*Usual symbol*	*Usual unit*
length	*l, h, d, s, x*	km, m, cm, mm
area	*A*	m^2, cm^2
volume	*V*	m^3 cm^3, dm^3
weight	*W*	N
mass	*m, M*	kg, g
time	*t*	h min, s
density	*ρ*	g/cm^3, kg/m^3
speed	*u, v*	km/h, m/s, cm/s
acceleration	*a*	m/s^2
acceleration of free fall	*g*	m/s^2
force	*F*	N
gravitational field strength	*g*	N/kg
moment of force		N m
work done	*W*	J, kJ, MJ
energy	*E*	J, kJ, MJ, kW h
power	*P*	W, kW, MW
pressure	*p*	N/m^2, N/cm^2
temperature	*θ, T*	°C, K

[illegible]		
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
spring constant	*k*	[illegible]
momentum	*p*	[illegible]
impulse	*FΔt*	[illegible]
pressure	*p*	Pa
specific heat capacity	*c*	[illegible]

Core		
Quantity	*Usual symbol*	*Usual unit*
frequency	f	Hz, kHz
wavelength	λ	m, cm
focal length	f	m, cm
angle of incidence	i	degree (°)
angle of reflection	r	degree (°)
angle of refraction	r	degree (°)
critical angle	c	degree (°)
potential difference/voltage	V	V, mV, kV
current	I	A, mA
e.m.f.	E	V
resistance	R	Ω
charge	Q	C
count rate		count/s, counts/minute
half-life		s, minutes, h, days, weeks, years

[illegible]		
Quantity	Usual symbol	[illegible]
wavelength	λ	nm
refractive index	n	
Hubble constant	H_0	s^{-1}

Glossary

Command words

Below are the Cambridge International definitions for command words which may be used in exams.

The information in this section is taken from the Cambridge Assessment International Education syllabus (0625/0972) for examination from 2023. You should always refer to the appropriate syllabus document for the year of your examination to confirm the details and for more information. The syllabus document is available on the Cambridge Assessment International Education website www.cambridgeinternational.org.

calculate: work out from given facts, figures or information

comment: give an informed opinion

compare: identify/comment on similarities and/or differences

deduce: conclude from available information

define: give precise meaning

describe: state the points of a topic; give characteristics and main features

determine: establish an answer using the information available

explain: set out purposes or reasons; make the relationships between things evident; provide why and/or how and support with relevant evidence

give: (a reason/example) produce an answer from a given source or recall/memory

identify: name/select/recognise

justify: support a case with evidence/argument

predict: suggest what may happen based on available information

sketch: make a simple freehand drawing showing the key features, taking care over proportions

state: express in clear terms

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations

Key words

a.c. generator: a device such as a dynamo used to generate alternating current.

absolute zero: the temperature at which particles have no kinetic energy.

absorption spectrum: dark lines in a spectrum that are produced when light passing through cooler gas is absorbed.

acceleration due to gravity: the acceleration of an object falling freely under gravity.

acceleration of free fall: the acceleration of an object falling freely under gravity.

acceleration: the rate of change of an object's velocity.

accretion: the coming together of matter under the influence of gravity to form larger bodies.

accretion disc: a rotating disc of matter formed by accretion.

activity: the rate at which nuclei decay in a sample of a radioactive substance.

air resistance: friction acting on an object moving through air.

alpha decay: the decay of a radioactive nucleus by the emission of an α-particle.

alpha particle (α-particle): a particle made up of two protons and two neutrons; it is emitted by an atomic nucleus during radioactive decay.

alternating current (a.c.): electric current that (periodically) changes direction in a circuit.

ammeter: a meter for measuring electric current.

ampere, amps (A): the SI unit of electric current.

amplitude: the greatest height or depth of a wave from its undisturbed position.

analogue signal: a signal which varies continuously in frequency and amplitude.

analogue: a display that has hands (or a needle) and is often not very precise.

angle of incidence: the angle between the incident ray and the normal drawn at the point where the ray hits the surface.

angle of reflection: the angle between the reflected ray and the normal drawn at the point where the ray hits the surface.

angle of refraction: the angle between a refracted ray and the normal to the surface at the point where it passes from one medium to another.

anticlockwise: turning in the opposite direction from the hands on a clock.

armature: the moving part of an electromagnetic device such as a relay or bell.

asteroids and meteoroids: lumps of rock which orbit the Sun.

atom: the smallest part of an element that can exist.

attractive forces: forces between particles which hold the particles in fixed positions in a solid.

average speed: the speed calculated from total distance travelled divided by total time taken.

axis: the imaginary line between the Earth's North and South poles.

background radiation: the radiation from the environment to which we are exposed all the time.

bar magnet: a rectangular-shaped permanent magnet with a north pole at one end and a south pole at the other.

battery: two or more electrical cells connected together in series.

beta decay: the decay of a radioactive nucleus by the emission of a β-particle.

beta particle (β-particle): a high speed electron that is emitted by an atomic nucleus during radioactive decay

Big Bang theory: the Universe (space, time, matter, energy) was created at a single point 13.8 billion years ago and has been expanding and cooling ever since.

biofuel: material, recently living, used as a fuel.

black hole: the final stage in the life cycle of a star that started with more than eight solar masses; it has enough mass left over after exploding as a supernova to collapse to a point where gravity is so strong that not even light can escape.

boiler: device where thermal energy is transferred to water to turn it into steam.

boiling point: the temperature at which a liquid changes to a gas (at constant pressure).

boiling: changing from liquid to gas at a fixed temperature called the boiling point.

bonds: another name for the forces between particles.

Brownian motion: the motion of small particles suspended in a liquid or gas, caused by molecular bombardment.

calibrate: to mark a standard scale on to a measuring instrument

calibrated: should agree closely with a standard or agrees when correction applied

cell: a device that provides an electromotive force (e.m.f in a circuit by means of a chemical reaction.

centre of gravity: all the mass of an object could be located here and the object would behave the same (when ignoring any spin).

changes of state: changing from one state of matter to another.

charge: carried around a circuit by the current; negative charge is carried by electrons.

chemical energy: energy stored in bonds between atoms that can be released when chemical reactions take place

clockwise: turning in the same direction as the hands of a clock.

collision: the meeting of particles or of bodies in which each exerts a force upon the other.

comet: a ball of ice, dust and gas which orbits the Sun i a highly elliptical orbit.

commutator: a device used to allow current to flow to and from the coil of a d.c. motor or generator.

compression: a region of a sound wave where the particles are pushed together

condensing: changing from gas to liquid.

conductor: a material that allows an electric current to flow through it.

contaminated: when an object has acquired some unwanted radioactive substance.

convection current: the transfer of thermal energy by th motion of a fluid.

convection: the transfer of thermal energy through a material by the movement of the material itself.

conventional current: the direction positive charges would flow in a complete circuit, from the positive to negative terminals of a cell, and opposite to the direction that electrons flow.

converging lens: a lens that causes rays of light parallel to the axis to converge at the principal focus.

coulomb (C): the SI unit for electric charge.

count rate: the number of decaying radioactive atoms detected each second (or minute, or hour).

crest: (or peak) the highest point of a wave.

critical angle: the minimum angle of incidence at which total internal reflection occurs.

current: the rate at which electric charge passes a point in a circuit.

current–voltage characteristic: a graph of current on the vertical axis and voltage on the horizontal axis.

density: the ratio of mass to volume for a substance.

diffraction: when a wave spreads out as it travels through a gap or past the edge of an object

digital signal: a signal that consists of a series of pulses which are either on or off.

digital: a display that shows numbers and is often precise.

diminished: used to describe an image which is smaller than the object.

diode: an electrical component that allows electric current to flow in one direction only

direct current (d.c.): electric current that flows in the same direction all the time.

dispersion: the separation of different wavelengths of light because they are refracted through different angles.

displace: moving something to another place so water is moved out of the way (upwards) when an object is lowered into it.

dissipated: energy that is spread out becomes not useful or wanted.

diverging lens: a lens that causes rays of light parallel to the axis to diverge from the principal focus.

doing work: transferring energy by means of a force.

double insulated: when the electric circuit for an electrical appliance is placed inside a case made from an electrical insulator so that it is impossible for a live wire to touch the outer casing.

drag: friction that acts on an object as it moves through a fluid (a liquid or a gas).

earthed: when the case of an electrical appliance is connected to the earth wire of a three-pin plug; the earth wire is electrically connected to the ground to prevent current passing through anyone touching a faulty appliance.

eccentricity: a measure of how elliptical an orbit is.

efficiency: the fraction (or percentage) of energy supplied that is usefully transferred

electric field: a region of space in which an electric charge will experience a force.

electrical conductor: a substance that allows the flow of electrons (electrical current).

electrical insulator: a substance that inhibits the flow of electrons (electrical current).

electrical power: power = current × p.d ($P = VI$).

electromagnet: a coil of wire that acts as a magnet when an electric current passes through it.

electromagnetic induction: the production of an e.m.f. across an electrical conductor when there is relative movement between the conductor and a magnetic field

electromagnetic radiation: energy that is transferred using electromagnetic waves.

electromagnetic spectrum: the family of radiations similar to light.

electromotive force (e.m.f.): the electrical work done by a source (cell, battery etc.) in moving (a unit) charge around a circuit; the voltage across the terminals of a source.

electron: a negatively charged particle, smaller than an atom.

electron charge: the electric charge of a single electron $= -1.6 \times 10^{-19}$ C.

electrostatic charge: a property of an object that causes it to attract or repel other objects with charge.

ellipse: a squashed circle.

energy: quantity that must be changed or transferred to make something happen.

enlarged: used to describe an image which is bigger than the object.

(the) Equator: an imaginary line drawn round the Earth halfway between the North Pole and the South Pole.

equilibrium: when no net force and no net moment act on a body.

evaporation: changing from a liquid to a gas at any temperature.

event: something that happens or takes place, often at a specific time and place.

extension: the increased length of an object (for example, a spring) when a load (for example, weight) is attached to it.

fixed points: known values used to calibrate a measuring instrument

Fleming's left-hand rule: a rule that gives the relationship between the directions of force, field and current when a current flows across a magnetic field.

Fleming's right-hand rule: a rule that gives the relationship between the directions of force, field and current when a current flows across a magnetic field.

fluid: a substance which can flow; liquids and gases are fluids.

focal length: the distance from the centre of the lens to its principal focus.

force: the action of one body on a second body; unbalanced forces cause changes in speed, shape or direction.

fossil fuels: material, formed from long-dead material, used as a fuel.

frequency: the number of vibrations or waves per unit of time.

friction: the force that acts when two surfaces rub over one another.

fuse: a device that breaks the circuit if the current exceeds a certain value; it is a piece of metal wire that melts when too much current flows through it.

galvanometer: a meter for measuring tiny electric current.

gamma ray (γ-ray): electromagnetic radiation emitted by an atomic nucleus during radioactive decay.

generator: a device which generates electricity using electromagnetic induction.

geothermal energy: energy stored in hot rocks underground.

gravitational field strength: is the gravitational force exerted per unit mass placed at that point.

gravitational potential energy (g.p.e): the energy store of an object raised up against the force of gravity; more generally, it is the distance between particles or bodies.

gravity: the force that exists between any two objects with mass.

half life: the average time taken for half the atoms in a sample of a radioactive material to decay.

hard (material): a material that, once magnetised, is difficult to demagnetise.

hemisphere: half of a sphere; the Earth can be considered to be made of two hemispheres divided by the Equator.

hertz: the unit of frequency; 1 Hz =1 wave per second.

Hooke's law: the extension of an object is proportional to the load producing it

Hubble constant: the slope of a graph of galaxy speed against distance.

Hubble time: the inverse of the Hubble constant, which gives an estimate for the age of the Universe.

Hubble's law: distant galaxies are moving away from Earth with a speed, v, that is proportional to their distance, d, from Earth; $v = H_0 d$ where H_0 is the Hubble constant.

image: what we see when we view an object by means of reflected rays.

immerse: to cover something in a fluid (usually water) so that the object is submerged.

impulse: the change in an object's momentum, $F\Delta p$, or the force acting on an object multiplied by the time for which the force acts ($F \times t$).

incident ray: a ray of light arriving at a surface.

induced e.m.f.: (or induced voltage) the e.m.f. created in a conductor when it cuts through magnetic field lines.

induced magnetism: when a magnetic material is only magnetised when placed in a magnetic field (for example, when brought close to the pole of a permanent magnet).

infrared radiation: electromagnetic radiation whose wavelength is greater than that of visible light; sometimes known as thermal radiation.

insulator: a material that makes it very difficult for an electrical current to flow through it.

internal energy: the energy of an object; the total kinetic and potential energies of all of its particles.

internal reflection: when a ray of light strikes the inner surface of a material and some of it reflects back inside it.

interrupt card: allows the speed of an object passing through a light gate to be calculated; a timer starts when the card breaks the beam and stops when the beam is no longer broken.

interstellar cloud: a cloud of gas and dust that occupies the space between stars.

inversely proportional: two quantities are inversely proportional when increasing one quantity decreases the other by the same factor; doubling one quantity halves the other.

inverted: used to describe an image which is upside down compare to the object.

ionisation: when a particle (atom or molecule) becomes electrically charged by losing or gaining electrons.

ionising nuclear radiation: radiation, emitted by the nucleus which can cause ionisation; alpha or beta particles, or gamma rays.

irradiated: when an object has been exposed to radiation.

isotope: isotopes of an element have the same proton number but different nucleon numbers.

joule (J): the SI unit of transferred energy (or work done); work done is the force of one newton (1 N) when applied through a distance of one metre (1 m); 1 J = 1 N m.

Kelvin temperature scale: (or the absolute temperature scale) the temperature measured from absolute zero. A difference in temperature of 1 kelvin is the same as a difference of 1 C. 0 K is approximately –273 °C.

kinetic energy: the energy store of a moving object.

kinetic particle model of matter: a model in which matter consists of moving particles.

lamina: flat two-dimensional shape.

laser: a device for producing a narrow beam of light of a single colour (monochromatic) or wavelength.

laterally inverted: an image in which left and right have been reversed.

Lenz's law: the direction of an induced current always opposes the change in the circuit or the magnetic field that produces it.

light gates: allow the speed of an object passing between them to be calculated electronically.

light-dependent resistor (LDR): a device whose resistance decreases when light shines on it.

light-emitting diode (LED): a type of diode that emits light when a current flows through it.

light-year: the distance travelled in space by light in one year (it is equivalent to about 9.5×10^{5} m).

limit of proportionality: up to this limit, Hooke's law is obeyed (so extension is proportional to load).

load: the force (usually weight) stretches an object (a spring)

longitudinal wave: a wave in which the vibration is forward and back, parallel to the direction of propagation of the wave.

lubrication: usually a liquid, it allows two surfaces to slide past each other more easily.

magnetic field lines: represent the direction the magnetic force would have on the north pole of a magnet.

magnetic field: a region of space around a magnet or electric current in which a magnetic pole experiences (feels) a force.

magnetised: when a magnetic material has been made magnetic.

main sequence: a stable star that is burning hydrogen in its core; once it has used up 12% of its hydrogen it goes onto another stage of its life cycle.

mass: is the quantity of matter a body is composed of; mass causes the object to resist changes in its motion and causes it to have a gravitational attraction for other objects.

melting point: the temperature at which a solid melts to become a liquid.

melting: changing from solid to liquid.

meniscus: curved upper surface of a liquid.

minor planet: an object which orbits the Sun but is not large enough or far enough from another object to be defined as a planet.

model: a way of representing a system in order to understand how it functions, usually mathematical.

molecular cloud: a cloud of interstellar gas that consists mostly of molecular hydrogen and is cold and dense enough to collapse to form stars.

molecule: two or more atoms joined together by chemical bonds.

moment: the turning effect of a force about a pivot; given by force × perpendicular distance from the pivot...

momentum: the quantity mass × velocity, $p = mv$.

monochromatic: describes a ray of light (or other electromagnetic radiation) of a single wavelength.

motor effect: when current flows in a wire in a magnetic field which is not parallel to the current, a force is exerted on the wire.

national grid: the system of power lines, pylons and transformers used to carry electricity around a country

negative charge: the type of electric charge carried by electrons.

neutral: having no overall positive or negative charge

neutron number (N): number of neutrons in the nucleus of an atom

neutron star: a collapsed star composed almost entirely of neutrons which forms when a star with more than eight solar masses reaches the end of its life.

neutron: an uncharged particle found in the atomic nucleus.

newton (N): the force required to give a mass of 1 kg an acceleration of 1 m/s²

non-renewables: an energy resource that is gone forever once it has been used.

normal: the line drawn at right angles to a surface at the point where a ray hits the surface.

NTC thermistor: a resistor whose resistance decreases with increasing temperature.

nuclear energy: energy stored in the nucleus of an atom.

nuclear fission: the process by which energy is released by the splitting of a large heavy nucleus into two or more smaller nuclei.

nuclear fusion: the process by which energy is released when two small light nuclei join together to form a new heavier nucleus.

nucleon number (A): (or mass number) the number of nucleons (protons and neutrons) in an atomic nucleus.

nucleon: a particle found in the atomic nucleus; a proton or a neutron.

nucleus: small, dense, positively charged region at the centre of an atom.

observations: what you see happening in an experiment.

ohm (Ω): the SI unit of electrical resistance; 1 Ω = 1 V/A.

ohmic resistor: has a constant resistance; its I–V characteristic is a straight line, so that the current through it is directly proportional to the voltage across it.

orbit: the path of an object as it moves around a larger object.

orbital period: the time taken for a planet to complete one full orbit of the Sun.

orbital radius: the average distance of the planet from the Sun.

oscillation: a repetitive motion or vibration.

pascal: the SI unit of pressure, equivalent to one newton per square metre; 1 Pa = 1 N/m^2 = 1 Pa.

period: the time for one complete oscillation or wave; the time it takes an object to return to its original position

permanent magnet: magnetised magnetic material that produces its own magnetic field that does not get weaker with time.

phases of the Moon: the different ways the Moon looks when viewed from Earth over a period of one month.

pivot: the fixed point about which a lever turns, also known as the fulcrum.

plane mirror: (or flat mirror) a mirror with a flat, reflective surface.

planet: a large spherical object that orbits the Sun without another similar object close to it.

planetary nebula: a bubble of gas surrounding a white dwarf star that used to be the outer shell of a red giant from which it collapsed.

plasma: a completely ionised gas in which the temperature is too high for neutral atoms to exist so it consists of electrons and positively-charged atomic nuclei.

plotting compass: very small compass with a needle that lines up with magnetic field lines, allowing changes in field direction to be observed and plotted over a very short distance.

plum pudding model: a disproved model of the atom which imagined it to consist of a positive 'pudding' with electrons dotted through it.

plumb bob: a mass (usually lead) hanging from a string to define a vertical line.

positive charge: the type of electric charge carried in the nucleus of an atom.

potential difference (p.d.): the work done by (a unit) charge passing through an electrical component; another name for the voltage between two points.

potential divider: part of a circuit consisting of two resistors connected in series to obtain a smaller voltage than supplied

power lines: cables used to carry electricity from power stations to consumers.

power: the rate at which work is done, or the rate at which energy is transferred.

precise: when several readings are close together when measuring the same value.

pressure: the force acting per unit area at right angles to a surface.

primary coil: the input coil of a transformer.

principal axis: the line passing through the centre of a lens perpendicular to its surface.

principal focus: (or focal point) the point at which rays of light parallel to the axis converge after passing through a converging lens.

principle of conservation of energy: energy cannot be created or destroyed; it can only be stored or transferred.

principle of the conservation of momentum: the total momentum is constant and does not change because of an interaction between bodies (such as collisions).

principle of moments: when an object is in equilibrium, the sum of anticlockwise moments about any point equals the sum of clockwise moments about the same point.

process: a series of actions or steps, often taking place over a long period of time.

proton: a positively charged particle found in the atomic nucleus.

proton charge: the electric charge of a single proton = $+1.6 \times 10^{19}$ C.

proton number (Z): (or atomic number) the number of protons in an atomic nucleus.

protostar: a very young star that is still gathering mass from its parent molecular cloud

P-waves: fast moving, longitudinal seismic waves.

radiation pressure: the outward force due to the high temperature of the star.

radiation: energy spreading out from a source carried by particles or waves.

radioactive decay: the emission of alpha, beta or gamma radiation from an unstable nucleus.

radioactive substance: a substance that decays by emitting radiation from its atomic nuclei

radioactive tracing: using a radioisotope to investigate a problem.

radiocarbon dating: a technique that uses the known rate of decay of radioactive carbon-14 to find the approximate age of an object made from dead organic material.

radioisotope: a radioactive isotope of an element.

random process: a process that happens at a random rate and in random directions; the timing and direction of the next emission cannot be predicted.

rarefaction: a region of a sound wave where the particles are further apart.

ray box: apparatus used to produce a ray of light.

ray diagram: a diagram showing the path of rays of light.

ray: a narrow beam of light.

real image: an image that can be formed on a screen.

red giant: a star that began with fewer than eight solar masses and is burning helium in its core; its shell of hydrogen has expanded and cooled.

red supergiant: similar to red giants, they form when stars with eight times the mass of the Sun run out of hydrogen fuel in their core but fusion of hydrogen continues in the outer shells

redshift: an increase in the observed wavelength of electromagnetic radiation (including visible light) from a star or galaxy because it is moving away from us.

reflected ray: a ray of light which has been reflected from a surface.

reflection: the change in direction of a ray or wave when it strikes a surface without passing through it.

refraction: the bending of light when it passes from one medium to another

refractive index: the ratio of the speeds of a light wave in two different media.

relative charge: the charge of a particle relative to the charge of a proton.

relative mass: the mass of a particle relative to the mass of a proton.

relay: a switch operated by an electromagnet.

renewables: an energy resource that will be replenished (replaced) naturally when used.

resistance: a measure of how difficult it is for an electric current to flow through a device or a component in a circuit; it is the p.d. across a component divided by the current through it.

resistor: a component in an electric circuit whose resistance decreases the current flowing.

resultant force: the single force that has the same effect on a body as two or more forces.

right-hand grip rule: a rule which gives the direction of field lines around a straight wire when a current flows through it.

ripple tank: a shallow water tank used to demonstrate how waves behave.

ripple: a small uniform wave on the surface of water.

Sankey diagram: a flow diagram that represents the principle of conservation of energy: the width of the arrows is proportional to energy.

scalar quantity: something that has magnitude but no direction

scatter graph: a way displaying two sets of data to see if there is a correlation, or connection.

secondary coil: the output coil of a transformer.

seismic waves: waves caused by earthquakes.

slip rings: a device used to allow current to flow to and from the coil of an a.c. generator.

soft (material): a material that, once magnetised, is easy to demagnetise.

solar cell/photocell/photovoltaic cell: an electrical device that transfers the energy of sunlight directly to electricity, by producing a voltage when light falls on it.

solar mass: equal to the mass of the Sun (2×10^{30} kg).

solar panel: used to collect energy that is transferred by light from the Sun.

solenoid: an electromagnet made by passing a current through a coil of wire.

solid friction: the resistance to motion caused when two surfaces are in contact.

solidifying: (or freezing) changing from liquid to solid.

specific heat capacity: the energy required per unit mass per unit temperature increase.

spectrum: (plural 'spectra') waves, or colours, of light, separated out in order according to their wavelengths.

speed of light: the speed at which light travels (usually in a vacuum: 3.0×10^8 m/s).

speed: the distance travelled by an object per unit time

spring constant: is the constant of proportionality in Hooke's law and is a measure of the stiffness of a spring.

stable: an object that is unlikely to topple over, often because it has a low centre of gravity and a wide base.

stable star: a star that is not collapsing or expanding because the inward force of gravity is balanced by radiation pressure, which pushes outwards.

standard: is an absolute or primary reference or measurement.

states of matter: solid, liquid or gas.

static electricity: electric charge held by a charged insulator

step-down transformer: a transformer which decreases the voltage of an a.c. supply.

step-up transformer: a transformer which increases the voltage of an a.c. supply

strain energy: (or elastic energy) energy stored in the changed shape of an object.

supernova: an exploding star that began life with more than eight solar masses and has run out of fuel

S-waves: slow moving, transverse seismic waves.

temperature: a measure of how hot or cold something is; a measure of the average energy of the particles in a substance.

terminal velocity: the greatest speed reached by an object when moving through a fluid.

thermal conduction: the transfer of thermal energy by the vibration of molecules

thermal conductor: a substance that conducts thermal energy

thermal energy: energy transferred from a hotter place to a colder place because of the temperature difference between them.

thermal expansion: the increase in volume of a material when its temperature rises.

thermal insulator: a substance that conducts very little thermal energy.

total internal reflection (TIR): when a ray of light strikes the inner surface of a material and 100% of the light reflects back inside it.

transformer: a device used to change voltage of an a.c. electricity supply

transverse wave: a wave in which the vibration is at right angles to the direction of propagation of the wave.

trip switch: safety device that includes a switch that opens (trips) when a current exceeds a certain value.

trough: the lowest point of a wave.

turbine: a device that is made to turn by moving air, steam or water; often used to generate electricity.

turning effect: when a force causes an object to rotate or would make the object rotate of there were no resistive forces.

ultrasound: any sound with a frequency higher than 20 000 Hz

ultraviolet radiation: electromagnetic radiation with a wavelength shorter than that of visible light

unmagnetised: when a magnetic material has not been made magnetic.

unstable: an object that is likely to topple over, often because it has a high centre of gravity and a narrow base.

upright: used to describe an image which is the same way up as the object

variable resistor: a resistor whose resistance can be changed, for example by turning a knob or moving a slider.

vector quantity: has both magnitude (size) and direction.

vector triangle: a graphical representation of vectors in two dimensions so that the resultant vector can be calculated

velocity: the speed of an object in a stated direction.

virtual image: an image that cannot be formed on a screen.

voltage: the energy transferred or work done per unit charge; it can be imagined as the push of a battery or power supply in a circuit

voltmeter: a meter for measuring the p.d. (voltage) between two points.

volts (V): the SI unit of voltage (p.d. or e.m.f.); 1 V = 1 J/C.

volume: the space occupied by an object.

water cycle: water evaporates from the surface of the Earth, rises into the atmosphere, cools, condenses, and falls as rain.

watt (W): the unit of power when 1 J of work is done per unit time; 1 W = 1 J/s.

wave speed: the speed at which a wave travels.

wavefront: a line joining adjacent points on a wave that are all in step with each other.

wavelength: the distance between two adjacent crests (or troughs) of a wave.

weight: the downward force of gravity that acts on an object because of its mass.

white dwarf: the final stage of a star that started with fewer than eight solar masses when all its fuel has been used up.

work done: the amount of energy transferred when one body exerts a force on another; the energy transferred by a force when it moves; work done = energy transferred.

Key equations

acceleration = $\frac{\text{change in velocity}}{\text{time taken}}$

$a = \frac{\Delta v}{\Delta t}$

acceleration of free fall (m/s^2) = $\frac{\text{gradient}}{2}$

acceleration of free fall = $g = \frac{W}{m}$

average: the average of 12, 15 and 16 is 14.3:

$\frac{12 + 15 + 16}{3} = 14.3$

average orbital speed = $\frac{2 \times \pi \times \text{orbital radius}}{\text{orbital period}}$

$v = \frac{2\pi r}{T}$

$c = \frac{\Delta E}{m\Delta\theta}$

change in pressure = density × acceleration due to gravity × depth

$\Delta p = \rho g \Delta h$

conversion between Kelvin temperarure and degrees Celsius

T (K) = θ(°C) + 273

critical angle:

$n = \frac{1}{\sin c}$

current = $\frac{\text{charge}}{\text{time}}$

$I = \frac{Q}{t}$

density = $\frac{\text{mass}}{\text{volume}}$

efficiency = $\frac{\text{useful energy output}}{\text{total energy input}}$

energy transferred = current × p.d. × time

$E = IVt$

e.m.f. = $\frac{\text{work done on the charge}}{\text{charge}}$

$E = \frac{W}{Q}$

$\Delta E_k = \frac{1}{2}mv^2$

$\Delta E_p = mg\Delta h$

$g = \frac{4\pi^2}{G}$

$g = \frac{W}{m}$

gravitational potential of the lead = mass of lead × g × height of tube

impulse = force × time for which force acts

impulse = $F\Delta t = \Delta(mv)$

magnification = $\frac{\text{image height}}{\text{object height}} = \frac{u}{d}$

moment of a force = force × perpendicular distance from the pivot

momentum, $p = mv$

percentage efficiency = $\frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$

power, $p = \frac{\Delta E}{t}$

power = current × p.d.

$P = IV$

power in to primary coil = power out of secondary coil

$I_p \times V_p = I_s \times V_s$

power loss = square of current in the cable × resistance

$P = I^2R$.

pressure = $\frac{\text{force}}{\text{area}}$

$p = \frac{F}{A}$

p.d. = $\frac{\text{work done by the charge}}{\text{charge}}$

$V = \frac{W}{Q}$

refractive index:

$n = \frac{\sin i}{\sin r}$

relationship between pressure and volume for gas at a constant temperature:

pV = constant

resistance = $\frac{\text{p.d.}}{\text{current}}$

$R = \frac{V}{I}$

resistance for two resistors used as a potential divider:

$\frac{R_1}{R_2} = \frac{V_1}{V_2}$

resultant force = $\frac{\text{change in momentum}}{\text{unit time}}$

$F = \frac{\Delta p}{\Delta t}$

specific heat capacity = $\frac{\text{energy required}}{\text{mass} \times \text{change in temperature}}$

$c = \frac{\Delta E}{m\Delta\theta}$

specific heat capacity = $\frac{\text{energy required}}{\text{mass} \times \text{temperature increase}}$

$c = \frac{\Delta E}{m\Delta\theta}$

speed = $\frac{\text{distance}}{\text{time}}$

$v = \frac{s}{t}$

spring constant = $\frac{\text{force}}{\text{unit extension}}$

$k = \frac{F}{x}$

$\frac{\text{voltage across primary coil}}{\text{voltage across secondary coil}} = \frac{\text{number of turns on primary}}{\text{number of turns on secondary}}$

$\frac{V_p}{V_s} = \frac{N_p}{N_s}$

wave speed = frequency × wavelength

$v = f\lambda$

weight = mass × g

work done by a force = force × distance moved by the force in the direction of the force

$W = Fd = \Delta E$

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